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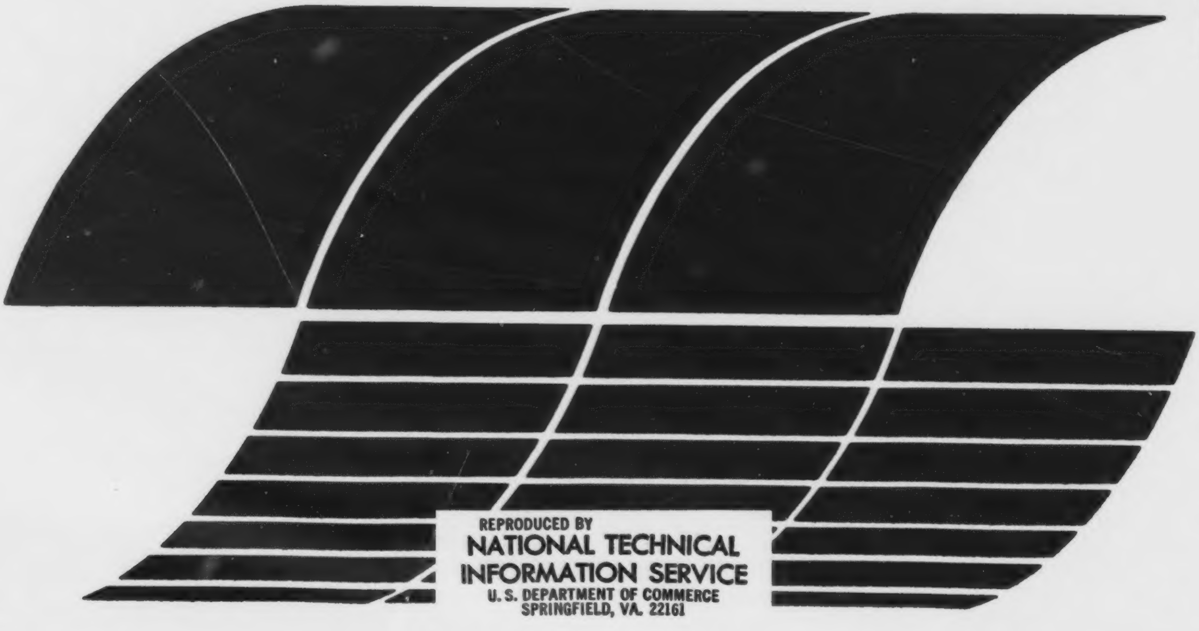

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16. ABSTRACT The report gives results of a study of energy conservation effects of point source recycle with high-temperature hyperfiltration (HF) in the textile industry. (HF and ultrafiltration (UF) are pressure-driven membrane processes which have potential for recycle of water, energy, and chemicals in wet finishing operations.) The reuse of water, energy, and chemicals can be best achieved if separations are applied to individual point-source streams rather than to total-plant mixed effluents. Five wet processes comprise a large fraction of total textile operations and require over half of the total energy used: preparation in rope and open-width ranges, and dyeing in continuous thermosol ranges, in pressure becks, and in atmospheric becks. Plant sites were visited and data taken on operations on which to base estimates of potential energy and materials to be saved. Each process effluent was sampled and analyzed to determine which membrane (HF or UF) should be used. Two small equipment skids allowed membrane operation at the plant sites. The permeate water in each case was reusable. Estimates of energy recoverable per mass of cloth processed (kJ/kg) for each operation are: rope preparation, 2646; open-width preparation, 5766; continuous dyeing, 2449; atmospheric beck dyeing, 20,115; high-pressure beck dyeing, 3910; and low-pressure beck dyeing, 1964.

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SUMMARY

Hyperfiltration and ultrafiltration are pressure driven membrane processes which have been shown to have potential for recycle of water, energy, and chemicals within textile wet finishing operations. This project follows two prior projects which showed (1) reusability of purified (permeate) and residual concentrate streams from hyperfiltration of spent dye water and (2) general reusability of permeate for a cross section of textile waste streams. The project began with the concept that reuse of water, energy, and chemicals would be most readily adopted if the separations were applied to individual point-source streams rather than total plant mixed effluents. It was apparent that the energy value in many spent streams was possibly sufficient to finance the cost and operation of the required equipment.

In consultation with plant personnel, five wet processes were selected which were estimated to comprise a large fraction of the energy and water use of current textile operations. These were preparation in rope ranges, preparation in open width ranges, dyeing in continuous thermosol ranges, dyeing in pressure becks, and dyeing in atmospheric becks. It is estimated that the energy used in these proceses comprises over half the total of all textile operations.

A team of researchers visited plant sites, received specifications from plant personnel, measured flow rates and temperatures and using the data with accepted engineering models calculated the energy use of the processes. Fundamental calculations of the evaporative heat loss were made for atmospheric becks and the open washtubs on a range. The energy fraction drained in effluent water was determined from which energy recoverable could be estimated. The results, on a basis of energy consumed per mass of cloth, are given in the following table together with the percentage estimated to be recoverable using membranes for water recovery.

Rope preparation	4337 kJ/kg (1860 Btu/lb)	61% recoverable
Open-width preparation	9300 kJ/kg (3990 Btu/lb)	62% recoverable
Continuous Dyeing (wet portions only)	3.95×10^3 kJ/kg (1690 Btu/lb)	62% recoverable
Atmospheric beck dyeing	4.47×10^4 kJ/kg (19170 Btu/lb)	45% recoverable
High pressure beck dyeing	1.15×10^4 kJ/kg (4930 Btu/lb)	34% recoverable
Low pressure beck dyeing	4.79×10^3 kJ/kg (2054 Btu/lb)	41% recoverable

Samples were taken of process effluent at each drain or of each drained fluid in a sequential process. Analysis of samples was used as a basis for decision on which process (UF or HF) to apply, and for guidance as to the conditions of operation. A drum size sample of each waste was shipped to the laboratory for screening tests to ascertain rejection and compatability of the membrane. These tests provided steering for the subsequent field tests.

Two small equipment skids were fabricated to allow membrane operation on fresh feed in the field. The hyperfiltration membrane modules were applied to atmospheric dye waste, dye fluid, and soaper fluid from continuous dyeing, and water desize, chemical desize, and caustic drains of the open width range. The ultrafiltration modules were applied to dye fluid and soaper fluid from continuous dyeing, to water wash in open width preparation, and to chemical desize wash in open width preparation.

The permeate water in each case was reported by plant personnel to be reusable. In the atmospheric dye becks and the dye range the residual fluid (membrane concentrate) showed some promise for reuse. Reuse of residual on the preparation range was not evaluated through water desize wash concentrate (PVA solutions) is being recycled in several locations in the industry. Thus the applicability of membranes for at least water recycle (with energy) has been demonstrated.

The long term flow properties as estimated from field data has been used to design (estimate the size of) prototype units. These designs form the basis for capital and operating cost estimates. Using a common economic basis for evaluating each system and a six year amortization of capital (selected arbitrarily), a simple total cost estimate has been formulated. Two of the fluids show negative costs (i.e., positive return) - the caustic washer of the preparation range and the soaper washer of the dye range. Small costs (net) are projected for chemical desize washer (preparation range) and larger costs for the water desize washer (preparation range) and the dye washer of the dye range. The atmospheric beck dye fluid could be operated at a cost savings or loss depending on whether a technical problem concerning an unusually large flux loss can be solved.

The impact of the environmental problem by each of the above membrane applications is (a) in concentrate reuse situations the individual contribution of the pollutants in the total stream is eliminated from the plant's discharge, (b) in all situations the waste hydraulic loading is lessened, reducing costs or promoting efficiency, or (c) process modifications may be developed which reduce chemical use or promote the use of superior products.

Several process modifications have been recognized which will enhance the membrane use through allowing lower costs of installation or will allow alternative processes or chemicals to be used thus reducing operating costs.

All processes studied have applicable modifications which appear to have some promise. Two such modifications have been demonstrated in full scale. The addition of dye in atmospheric beck dyeing to an already hot solution with the cloth is required to allow energy reuse. Through careful application of dye in a uniform and deliberate manner, a test dyeing was performed without the feared streaking effect. The open width preparation range was changed from high flow to lower flow by increasing the operating temperature. A net energy use decrease resulted and the effect on the membrane system cost projection is significant as well. The realization of the usefulness of superior washing to yield a lower flow requirement prompted a brief investigation of the washer equipment market and technology.

The incorporation of membranes for water recycle is viewed as promising. The energy benefit alone will pay for a substantial portion of the total cost. Membrane application to textile streams appears to be broadly feasible leading to a reduction in effluent volume of an estimated 38 percent based on the processes of this study and 90 percent or more if fully implemented. Thus membrane application allows a substantial step toward closed cycle operation. The interests of the EPA are served best by such closed cycle operation and the disposition of concentrate remains the principal hindrance to achievement of the zero discharge of liquid effluent.

This report was submitted in fulfillment of Grant R803875 by Clemson University under the sponsorship of the U. S. Environmental Protection Agency. This report covers a period from July 1975 to December 1978 and work was completed as of March 1979.

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Units and Conversions

Multiply English Unit	by	To Obtain Metric Quantity
Btu	1.0587 E+3	J (joule)
ft	3.048 E-1	m (meter)
ft^2	9.290 E-2	m^2
gal	3.785 E-3	m^3
fl ounce	2.957 E-5	m^3
pound (mass)	4.536 E-1	kg (kilogram)
psi	6.895 E+3	N/m^2 (Pascal)
gal/min	6.308 E-5	m^3/s
gal/ft^2-day (GFD)	4.716 E-7	m/s
ohm^{-1}	1.0	S/(siemens)
F minus 32	5/9	C (-K - 237.16)

Metric prefixes used

G (giga) $\equiv$ x 10^{9}
M (mega) $\equiv$ x 10^{6}
k (kilo) $\equiv$ x 10^{3}
d (deci) $\equiv$ x 10^{-1}
c (centi) $\equiv$ x 10^{-2}
m (milli) $\equiv$ x 10^{-2}
μ (micro) $\equiv$ x 10^{-6}

Thus the liter ($\equiv$ m^3/1000) is properly written as dm^3
The microm (10^{-6}m) is properly μm (micrometer)

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Four industrial plants contributed to the effort reported herein by supplying information, opening their plants for surveys, performing chemical and reuse analysis, allowing the operation of equipment at their expense, and other varied contributions. Their contributions are gratefully acknowledged. The plants are:

Graniteville Company, Gregg Division
M. Lowenstein & Sons, Lyman Printing and Finishing Company
Riegel Textile Corporation, La France Industries
Springs Mills, Grace Bleachery

Contributing significantly to portions of the effort were Dr. A. C. Elrod and Dr. P. J. Bishop, both Clemson University faculty.

This effort began through the interest and activity of T. N. Sargeant who was initially Project Officer, but who was transferred by EPA during the effort. The present Project Officer, Dr. Max Samfield, is acknowledged for his special effort required to carry through work in progress. His patience and continued support have been appreciated.

The extramural support of EPA-IERL in Cincinnati is acknowledged in the persons of Dr. Harry Bostian and Bob Mournighan. Each has played an active role in the execution of this grant.

INTRODUCTION

Hyperfiltration and ultrafiltration are membrane separation processes which produce a large stream dilute in solute and a small stream enriched in solute. Both types of membranes separate large molecular solutes and colloids; while only hyperfiltration is effective in separating small molecules. In this case, solutes include spent dyes, warp size, waxes and oils, various auxiliary chemicals and a host of contaminants. The membrane processes do not eliminate chemical discharge; rather, they provide a dilute (permeate) stream and a concentrate (residual) stream. The permeate was shown in two previous studies[1,2] to satisfy industrial water requirements. Further, in the first of these studies the concentrate was reused in commercial quality dyeing of various shades and a net decrease in dye use was projected.

In the previous studies mentioned, the membrane separation was applied to mixed effluent from the plant. It was apparent[3] that processing of the high temperature segregated streams would allow energy recovery and encourage the reuse of concentrate. In the many near-boiling temperature streams found in the textile industry, the energy value of the water is approximately ten times the value of the water.

Thus, the present program was conceived to identify candidate processes having high temperature streams and to study the applicability of membrane processes. The objective was to study the energy consumption of the selected processes and characterize the effluent from each appropriate source. Based on experience and screening tests of the fluids, a processing strategy was devised to test the best membrane/fluid combinations in the field for a period sufficient to evaluate long term effects on fresh fluid. Using the field data, economic studies were made

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[1] "Hyperfiltration for Renovation of Textile Finishing Plant Wastewater," by Craig A. Brandon and John J. Porter, EPA-600-2-76-060, March, 1976.

[2] "Hyperfiltration for Renovation of Composite Wastewater at Eight Textile Finishing Plants," by Craig A. Brandon, John J. Porter, and Donald K. Todd, Final Report, Grant S802973.

[3] "Application of High Temperature Hyperfiltration to Unit Textile Process for Direct Recycle," by Craig A. Brandon and Max Samfield, "Membranes: Desalination and Wastewater Treatment" conference, Jerusalem, 1978.

to estimate the net cost of application of membranes for industrial use.

Supporting the entire effort was an emphasis on process modifications. Some modifications result directly from recycle, i.e., recycled water is hot compared to water added cold and then heated. Other modifications, to washing processes particularly, include tradeoffs between flow and operating temperature to decrease membrane costs or permit the use of alternative chemical formulations.

CONCLUSIONS AND RECOMMENDATIONS

1. A survey of energy requirements and chemical discharge of the individual fluid streams from five common textile processes has been conducted. The aggregate of all such streams is estimated to comprise over half the energy utilization of the textile finishing operation.

2. It is estimated that approximately one half of the energy used in the processes studied can be effectively recovered by hyperfiltration or ultrafiltration if permeate recycle is adopted.

3. Screening tests were run on all but one fluid stream, followed by field tests on six fluid streams. It is considered that the long term effects were observed sufficiently to estimate costs on a reasonable basis.

4. All permeate water was determined reusable by the textile plant laboratory personnel. Simulation or estimation of build up effects was not attempted for the evaluation. Some of the concentrate streams were determined valuable for reuse.

5. A number of process modifications a) to permit membrane recovery processing, b) to reduce membrane equipment costs, and c) to allow chemical cost reductions were proposed.

6. Two full scale process modifications were demonstrated and are documented. Both were successful. In one, dyes were added at high temperatures without streaking. In the other, water use was diminished by operating at increased temperature - with a net energy decrease.

7. Based on membrane permeability observed in field testing, hypothetical designs were made and the respective costs estimated. Net operating costs and benefits were calculated. On the basis of six year amortization and without credit for chemical recovery, three of the six streams could offer payback potential on energy saved. The other three would be operated at a deficit. The average of the six streams is near a balance.

8. There is a general reluctance in management to adopt the risk associated with capital investment in the new membrane technology for the modest payback it affords.

9. There is a greater reluctance to consider the more difficult reuse of concentrated spent chemicals. Concentrate reuse will either

be adopted for its own value, as in the case of size recovery, or will be adopted after a permeate recovery unit is installed and the plant's laboratory further studies the concentrate for reuse. This is to say that management will probably not decide to install equipment if the payback depends on both permeate and concentrate energy recovery.

10. A membrane system may be considered on its merit as an energy recovery device. If the installation is to significantly reduce pollution (other than reducing total flow) a means of concentrate disposal must be devised. Since there is reluctance to vigorously pursue concentrate reuse, the technology of concentrate disposal should be studied by EPA. If such technology is adopted, the plants will, in time, learn how to "mine" their concentrated waste streams for raw materials and in the meantime pollution will be reduced by the action of the concentrate disposal.

11. Membrane processing may be particularly attractive for toxic laden streams. The concentrate from such streams will require special attention.

12. Depending on economic factors and EPA philosophy, a number of demonstration projects should be considered. By absorbing some of the risk, EPA can accelerate the application of the technology and stimulate the growth and interest of membrane manufacture and application.

1.0 ENERGY AND WATER CONSUMPTION OF SELECTED PROCESSES

In consultation with members of the South Carolina Textile Manufacturers Association and the Environmental Protection Agency five manufacturing processes were selected to include (1) as many as possible of the effluent guideline categories, (2) as many as possible of the wet manufacturing processes with "hot" wastewater, and (3) at least one case each of batch and continuous processing. The following five processes were selected for this study: (1) atmospheric beck process, (2) continuous preparation range, (3) pressure beck process, (4) continuous dye range, and (5) continuous (rope) preparation range. Four South Carolina industrial partners were involved: La France Industries, Lyman Printing and Finishing, Gregg Division of Graniteville, and Grace Bleachery of Springs Mills.

1.1 Atmospheric Beck Process

1.1.1 Process Description

Atmospheric beck dyeing is accomplished by exposing the fabric to a hot (82 to 96 C) dye solution for a sufficient length of time to achieve the desired shade of color. The procedure for dyeing a typical lot of cloth is as follows:

(1) Cold water is admitted to the dye beck (see Figure 1) and is heated to about 32 C.
(2) The cloth is loaded into the beck.
(3) Scouring (cleaning) chemicals are added to the water and, while the cloth is circulated through this solution, the solution temperature is increased to, and maintained at, about 71 C for about one-half hour.
(4) The scouring chemicals are flushed out of the beck and rinsed from the cloth. (This requires a large amount of cold water.)
(5) Fresh water again fills the beck and is heated to 32 C.
(6) The dye and auxiliary chemicals are added to the water.
(7) The solution is heated and maintained at about 87 C for sufficient time to color the cloth to the desired shade.
(8) The dye solution is flushed out of the beck and rinsed from the cloth. (This, again, requires much cold water.)
(9) Cold water is admitted to the beck again, and is heated to 32 C.
(10) Chemicals to make the dye "color fast" are added to the water.

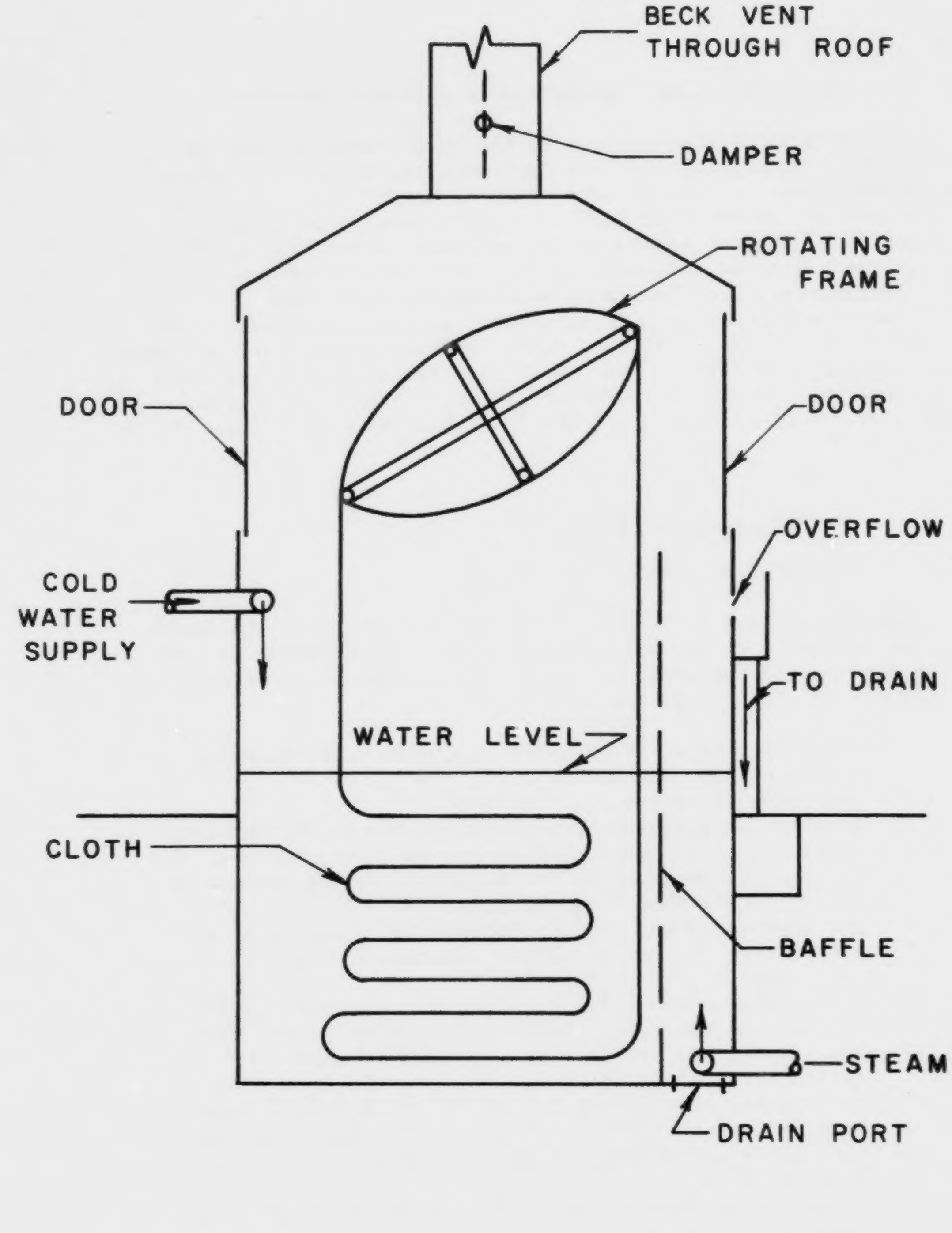
BECK VENT
THROUGH ROOF
DAMPER
ROTATING
FRAME
DOOR
DOOR
OVERFLOW
COLD
WATER
SUPPLY
TO DRAIN
WATER LEVEL
CLOTH
BAFFLE
STEAM
DRAIN PORT

FIGURE 1 SCHEMATIC DIAGRAM OF AN ATMOSPHERIC BECK

(11) This solution is heated to about 50 C and maintained at that temperature for about fifteen minutes.
(12) These dye "fixing" chemicals are flushed from the beck and carefully rinsed from the cloth. (Again, much cold water is used.)
(13) The cloth is unloaded from the dye beck and sent to a dryer.

Because different materials and dyes may be involved, certain procedures will vary from this thirteen-step generalization. However, all procedures are similar. Figure 2 plots temperature versus time for a typical cycle with scour.

The observed plant had 32 dye becks installed, ranging in width from 0.91 to 3.66m. These becks were operated randomly around the clock five days of each week. Normal operation had these becks dyeing 36 lots of cloth daily, with (typically) three becks undergoing maintenance at any one time. Then, on the average, each beck dyes 36/29 (or 1.24) lots of cloth each day. The length of time that a beck is kept at high temperature varies markedly from one lot of cloth to the next, but 6.6 hours is average. When one adds the time required for loading the beck with water and with cloth, time for controlled gradual heating up and cooling down, time for rinsing the cloth, time for sampling to determine whether the cloth has been dyed to the proper shade of color, and time for unloading the material from the beck, it is understandable that each beck averages dyeing only 1.24 lots of cloth daily.

1.1.2 Chemicals Used

Many various chemicals are used in the dyeing and scouring processes of the dyehouse. A sample of these chemicals is given below for three arbitrarily selected processes:

Dye and Scour Chemicals	$\frac{\text{kg mass of chemical used}}{\text{1000 kg of cloth processed}}$	
Process 2 - Formula 8545		
Dye	2.160	Dye Mixture
Salt	150.000	Salt Liquid
Fix	5.000	Acetic Acid
Process 11 - Formula 1191		
Dye Auxiliary	20.000	Quadye NT
Dye	27.400	Dye Mixture
Salt	150.000	Salt Liquid
Fix	20.000	Fix GD
Process 12 - Formula 1197		
Scour Chemicals	120.000	Peroxide
Scour Chemicals	10.000	Caustic Soda

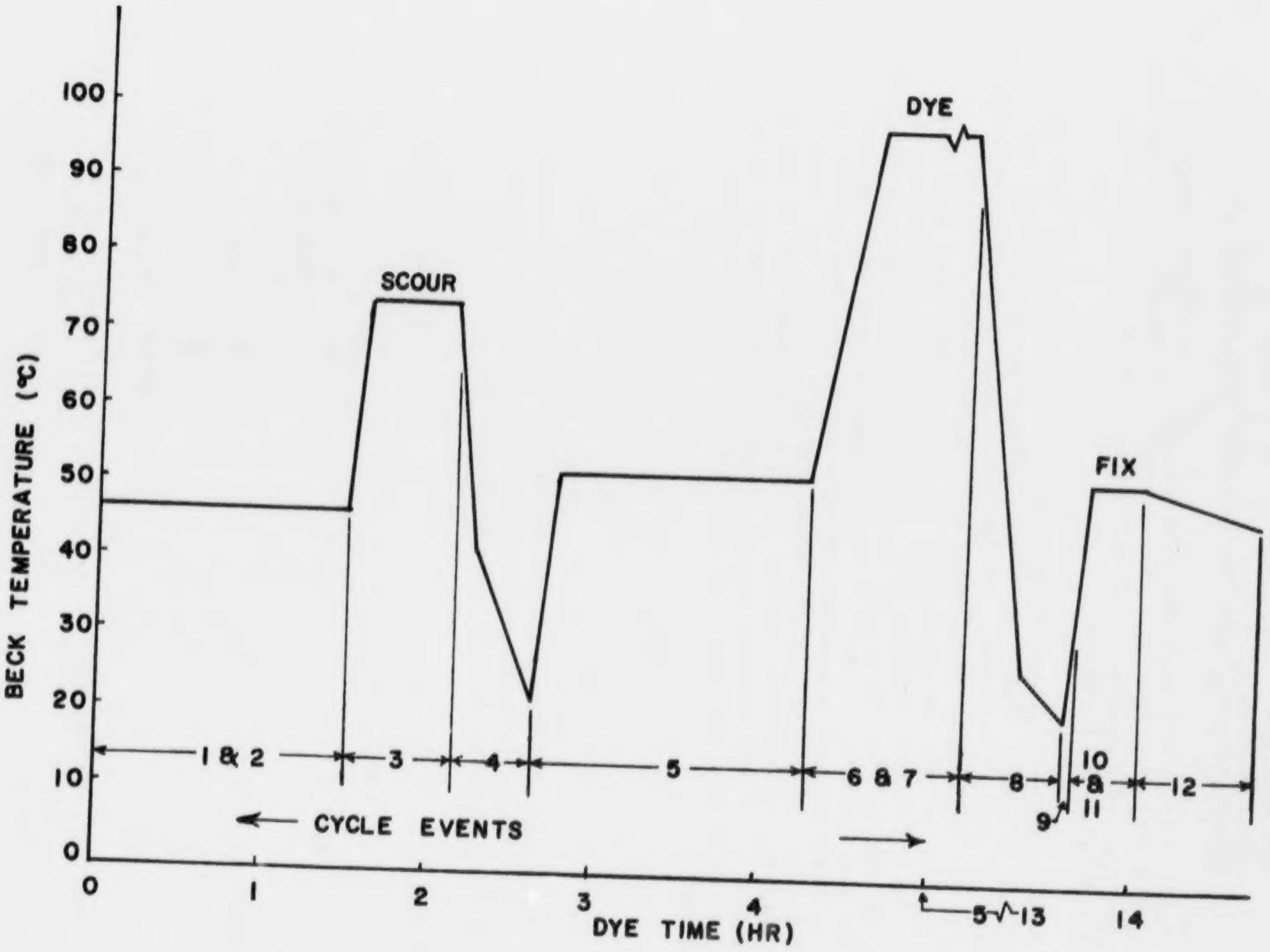

FIGURE 2 TYPICAL DYE CYCLE WITH SCOUR FOR ATMOSPHERIC BECK DYEING .

Dye and Scour Chemicals	kg mass of chemical used / 1000 kg of cloth processed	
Process 12 (continued)		
Scour Chemicals	10.000	Sodium Bisulfite
Dye Auxiliary	20.000	Quadye NT
Dye Auxiliary	2.500	Leveler 37-5
Dye	0.826	Dye Mixture
Salt	50.000	Glauber Salt
Fix	20.000	Fix GD

1.1.3 Energy and Water Use

Energy and water use in the dyehouse was studied to determine the potential for reclamation. During the course of this study two different methods were employed to calculate the energy and water consumed per kilogram of cloth processed. In the first method, an energy and water mass balance is made on the dyehouse without reference to the individual dyeing cycles. The dyehouse is taken as an entity and the total water and energy usage is calculated from the inlet and discharge water flow rates and temperatures and the steam consumption in the dyehouse. To better understand the distribution of energy, a second method is based on the analysis of selected hypothetical dye cycles to determine the energy and water consumed per kilogram of cloth processed during each cycle. Three cycles, two representing the average cycle (with or without scour) and the other a typical cycle (with scour), were studied through this method. Table 1 shows the summary of calculations for a single, typical dye cycle for illustrative purposes.

The results obtained by the two methods are given below. The details of the averaging of hypothetical cycles are given in Appendix C.

	Energy consumption per kg of cloth processed (kJ)	Water usage per kg of cloth processes (m^3)
Method I (overall balance)	4.47×10^4 (19,170 Btu/lb)	0.447 (53.7 gal/lb)
Method II (average hypothetical cycle)	4.57×10^4 (19,600 Btu/lb)	0.288 (34.6 gal/lb)

The calculations by each method agree well for energy but the hypothetical cycles fail to fully account for the water usage presumed to occur during sustained rinses.

1.2 Continuous Preparation Range

1.2.1 Process Description

TABLE 1. TYPICAL DYE CYCLE DETAILS - ATMOSPHERIC BECK

Event		1 & 2	3	4	5	6 &7	8 & 9	10 & 11	12
Duration	min	91.5	37.5	30.0	99.0	522.0	45.0	21.0	42.0
Temperature	°C	46	74	-	52	98	-	52	-
Energy consumption to heat from 18 C to operating temp	GJ	0.629	0.658	-	0.755	1.103	-	0.755	-
Energy consumption to maintain at operating temp	GJ	0.203	0.303	-	0.292	12.28	-	.061	-
Total energy consumption	GJ	0.832	0.961	-	1.047	13.38	-	.816	-
Water used	m^3	5.65 (hot)	0.27 (hot)	13.32 (cold)	5.7 (hot)	0.47 (hot)	26.1 (cold)	5.7 (hot)	23.5 (cold)

Cumulative energy = 17.0 GJ (16 x 10^6 Btu)
Cumulative water = 80.7 m^3 (21 kgal)
Beck volume (cold) = 5.40 m^3 (1428 gal)
297 kg of cloth processed

Energy = 57200 kJ/kg cloth (24,500 Btu/lb)

Water = 0.271 m^3/kg cloth (32.6 gal/lb)

The continuous preparation range prepares the cloth for subsequent finishing, i.e., dyeing or printing, through a series of chemical baths followed by high-temperature washing to "clean" the cloth. On the range observed conditioned cloth (greige cloth) from the heat-set oven initially enters a pair of Gaston County alternators that wash the cloth at 60 C with a flow rate of 5.14 dm^3/s (35 gal/min) to the drain on each washer. Then the cloth proceeds to a 60 C chemical bath, the desize saturator. After exposure to a steamer environment the cloth then enters the desize washers for a hot rinse. The three desize washers were operating at 82 C, and each washer has approximately 1.05 dm^3/s (17 gal/min) of fresh water run in at the nip sprays. The washers are counterflowed back toward the desize saturator before going to the drain. The cloth then proceeds to the second chemical bath (two caustic saturators, running at 77 C). This is followed by a steamer and J-box. Subsequently, the cloth enters the caustic washers for a second high-temperature bath. The caustic washers were operated at 82 C and counterflow back toward the caustic steamer. Each washer has nip sprays feeding the washers at approximately 1.05 dm^3/s (17 gal/min) on each washer. There are four washers in this section gravity counterflowing to a single drain. Then the cloth proceeds to the third and last chemical bath (the peroxide saturator) running at 46 C. After a steamer and J-box the cloth then enters the peroxide washers that were operating at 76 C for the last high-temperature bath. Upon exit it is ready for subsequent finishing. The four peroxide washers are counterflowed back toward the peroxide J-box, before going to the drain. The washers were fed by nip sprays at 0.79 dm^3/s (12.5 gal/min) on each washer. A schematic diagram of the flow arrangement on the continuous preparation range is given in Figure 3.

1.2.2 Chemicals Used

The formulations of the chemical baths used in the continuous preparation range are given below:

Desize Saturator (1)	0.5% Albone D.S. (stabilized peroxide)
	2.0% NaOH
	1.2% Superterge LRC-37 (detergent)
	1.8% Xylol
Caustic Saturator (2)	3.6% NaOH
	1.2% Superterge LRC-37
Peroxide Saturator (1)	2.5% Hydrogen Peroxide (50%)
	1.0% Sodium Silicate
	0.5% NaOH
	0.1% Superterge LRC-37
	0.1% Amquest 120-CF (chelate)

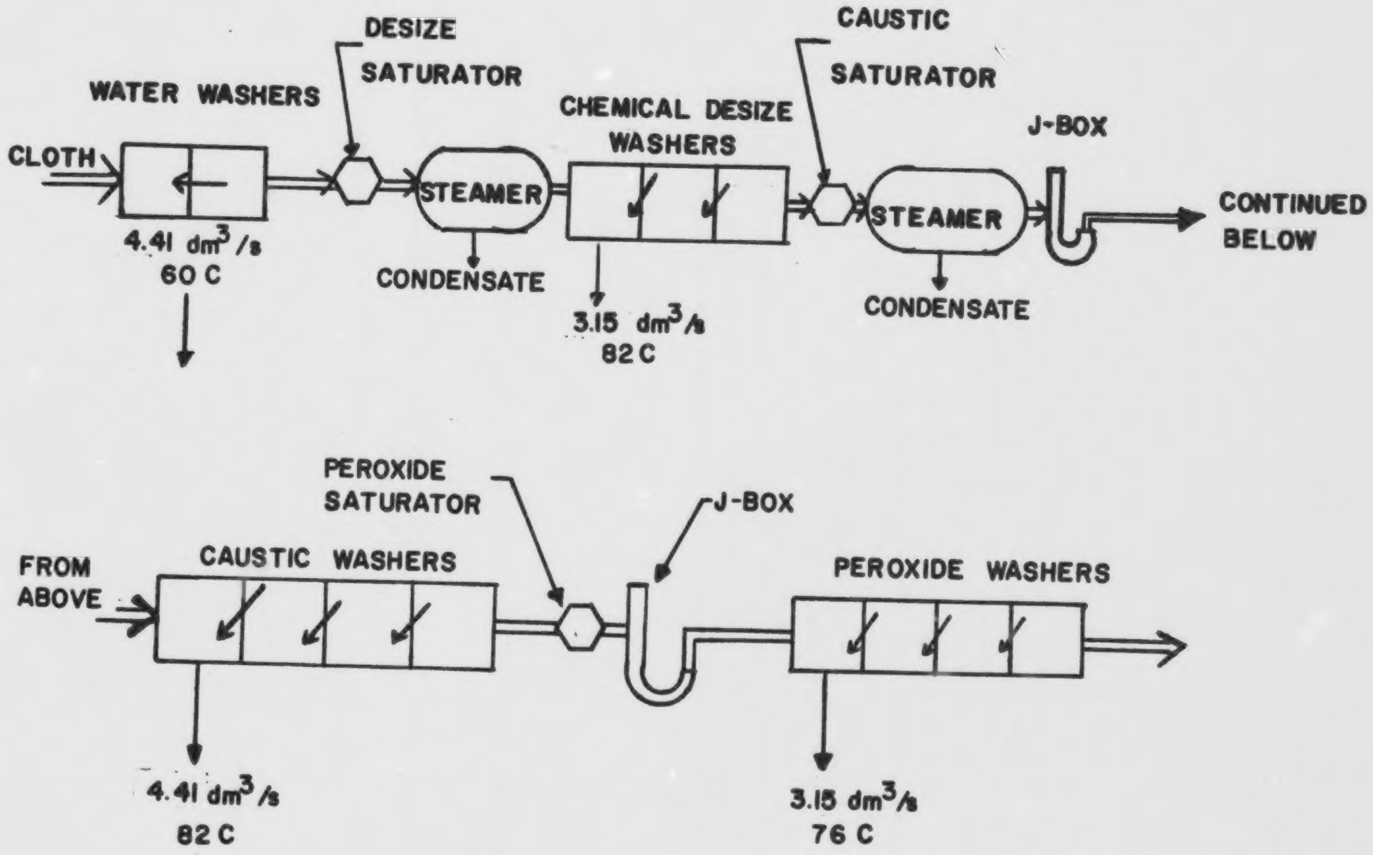
DESIZE
SATURATOR
CAUSTIC
SATURATOR
WATER WASHERS
CHEMICAL DESIZE
WASHERS
J-BOX
CLOTH
STEAMER
STEAMER
CONTINUED
BELOW
4.41 dm^3/s
60 C
CONDENSATE
3.15 dm^3/s
82 C
CONDENSATE
PEROXIDE
SATURATOR
J-BOX
FROM
ABOVE
CAUSTIC WASHERS
PEROXIDE WASHERS
4.41 dm^3/s
82 C
3.15 dm^3/s
76 C

FIGURE 3 SCHEMATIC DIAGRAM OF OPEN WIDTH PREPARATION RANGE

1.2.3 Energy and Water Consumption

An energy and water use study was made on the continuous preparation range to determine the energy and water consumption. The temperature data used in these calculations were obtained on January 30, 1976, (but the flows were determined over a year later after installation of instruments). Figure 3 presents the data used for analysis. Incoming water temperature was assumed to be 18 C which is considered to be the annual average.

The latent heat loss rates, q_T, were read from the curve of Figure A-5 corresponding to the appropriate operating temperatures for the wash tubs and saturators. This information along with estimated surface areas involved is given in Table 2. The net latent heat loss per unit area, for 9.11 m^2 of estimated cloth and water surface, is scaled to the loss rate for the 12.5 m^2 of the test washer. The latent heat loss, q_{lat}, was then calculated for the observed temperatures by

$$q_{lat} = q_{fig\ A\text{-}5}\ (9.11/12.5)$$

TABLE 2. EVAPORATIVE HEAT LOSS RATES FOR OPEN-WIDTH PREPARATION RANGE

Wash Box	Surface Area[a] (m^2)	Temperature (°C)	Heat Loss (GJ/hr)
GC #1	9.2	60	0.108
GC #2	9.2	60	0.108
SUBTOTAL			0.216
Desize Saturator	9.2	16	0.108
Desize Washer #1	9.2	87	0.354
Desize Washer #2	9.2	84	0.319
Desize Washer #3	9.2	82	0.281
SUBTOTAL			1.062
Caustic Saturator	9.2	82	0.288
Caustic Washer #1	9.2	49	0.066
Caustic Washer #2	9.2	67	0.153
Caustic Washer #3	9.2	73	0.200
Caustic Washer #4	9.2	82	0.288
SUBTOTAL			0.995
Peroxide Saturator	9.2	49	0.066
Peroxide Washer #1	9.2	89	0.384
Peroxide Washer #2	9.2	90	0.392
Peroxide Washer #3	9.2	82	0.393
Peroxide Washer #4	9.2	76	0.219
SUBTOTAL			1.344
TOTAL			3.62

[a] Each individual wash box has about 1.67 m^2 of water surface. The effective surface for evaporation is based on 49 linear meters of exposed cloth.

An estimate of the magnitude of convective and radiative heat transfer for the dye range was obtained using the equation

$$q = h\ A\ \Delta T.$$

The combined heat transfer coefficient, h, for radiation and convection was, from Appendix B, $11.3 W/m^2$-K (2 $Btu/hr/ft^2/F$). The environment temperature used was 29 C.

The energy loss by radiation and convection is given in Table 3 for the wash tubs and saturators for ideal and operating temperatures. The total energy loss by radiation and convection for observed operating temperatures was 0.534 GJ/hr.

TABLE 3. ENERGY LOSSES BY RADIATION AND CONVECTION

	Area (m^2)	Temperature (°C)	Energy Loss (GJ/hr)
GC Alternator	20.8	60	0.026
Desize Saturator	11.7	60	0.015
Steamer	30.2	99	0.086
Desize Washer	21.7	84	0.049
Caustic Saturator	11.7	82	0.025
Steamer	77.6	99	0.221
Caustic Washer	26.8	82	0.042
Peroxide Saturator	11.7	49	0.009
Peroxide Washer	26.8	84	0.060
TOTAL			0.533 (5.04×10^5 Btu/hr)

The energy loss to the drain (i.e., to heat water) was obtained by performing an energy flow calculation at the wash tub exists. The energy loss to the drain was obtained from

$$q_{drain} - (mc_p)_{H_2O}(T_{drain} - 18),$$

where 18 C is the incoming average annual fresh water temperature. Mass flow rates, drain temperatures, and corresponding energy losses to the drain are given in Table 4. Energy losses totaling about 12.7 GJ/hr (12 MBtu/hr) to the drain are calculated for the observed temperatures and flow rates.

The total amount of energy required to heat the water in the various operations plus the energy lost by radiation, convection, and evaporation was calculated to be 16.7 GJ/hr (16×10^6 Btu/hr) and is summarized in Table 5. The energy per unit of cloth was calculated for the observed cloth flow rate of 80 yards/min at 1.2 yards/lbm to be 9300 kJ/kg. The water used was 17.6 dm^3/s (240 gallons per minute) or 0.0243 m^3/kg (2.5 gallons per lbm) of cloth processed.

TABLE 4. ENERGY LOSS TO DRAIN

Wash Tub	Flow Rate (dm^3/s)	Temperature (°C)	Energy Loss (GJ/hr)
GC Alternator	4.41	60	2.77
Desize Washer	3.15	82	3.02
Caustic Washer	4.41	82	4.26
Peroxide Washer	3.15	76	2.72
TOTAL			12.7
			(12×10^6 Btu/hr)

TABLE 5. ENERGY SUMMARY - OPEN WIDTH PREPARATION RANGE

Item	Evaporation Loss	Radiation and Convection Loss	Energy To Drain	Total
GC Alternator	0.21	0.026	2.77	3.006
Desize Section	1.06	0.149	3.02	4.229
Caustic Section	1.00	0.289	4.26	5.549
Bleach Section	1.34	0.069	2.51	3.919
TOTAL	3.61	0.533	12.56	16.703
FRACTION OF TOTAL	21%	3%	76%	
	all values in GJ/hr		(16×10^6 Btu/hr)	

1.3 Continuous Dye Range

1.3.1 Process Description

The range observed in this study operates on cotton and cotton/synthetic blended fabrics. It is designed to process over 100,000 yards of fabric at a rate of 50-100 yards per minute. Other portions of the plant utilize continuous scouring, desizing, bleaching, and finishing equipment in addition to the continuous dye range being studied in this project.

The continuous dye process generally starts with fabric which has been heat-set, desized, scoured, bleached and dryed. The dry fabric is first passed into a dye solution and through a nip roll at the head end of the range where dye and chemicals are padded onto the fabric. The fabric is then dryed carefully with controlled infrared predryers and dry cans to prevent the migration of the dyes on the fabric. If the fabric contains polyester fiber the dye solution will contain dispersed dyes which must be fixed onto the polyester fiber after it is dryed. This is done in a thermosol oven at 204 to 215 C. The fabric is passed over rollers in this oven to give a total dwell time of 60 to 90 seconds. After leaving the oven the fabric passes over cooling cans to cool the fabric before it enters a chemical solution (caustic and hydro) to (chemically) reduce the vat dye already present on the fabric. A nip roll at the outlet side of the padder removes excess liquor from the fabric and it then enters a steamer at 104 C. The steamer provides the time, temperature, and moisture that is needed for the reduced vat dye to penetrate the cotton fiber. After leaving the steamer the fabric is passed through four rinse boxes to remove caustic and other chemicals from the fabric. The washing is not sufficient to remove the reduced vat dye from the cotton fiber but acts to remove caustic and reduction chemicals from the fiber before oxidation. This washing process increases cleanliness and reduces the chemical flow required in a bath which is applied next containing an oxidation agent and acid.

The oxidation may be performed with many chemicals; in the case under study potassium iodate is used with acetic acid. This solution completes the oxidation of the leuco vat dye to the insoluble form. The fabric then passes into a soap solution to aid in the crystallation of the vat dye to give the desired color and remove surface dye and chemicals from the fabric.

After the soap solution the fabric passes through three wash boxes which are used to completely rinse the fabric and adjust the final pH to 6-7 if the fabric is to be given a resin treatment. The fabric is then dryed and is ready for finishing if desired.

1.3.2 Chemicals Used

The chemicals utilized in the dye processes are shown in Table 6. Those judged possible to reclaim are designated therein.

TABLE 6. CHEMICAL UTILIZATION AND PROSPECTS FOR RECLAMATION

(A) Chemicals that are used for the continuous dye range	
Dyes	Chemicals
dispersed	sodium hydrosulfite
vat	caustic
sulfur	salt
reactive	antimigrants
	wetting agents - soap
	acetic acid
	buffering chemicals
	oxiding agent (periodate)
(B) Chemicals that may be recoverable	
wetting agents - soap	
salt	
acetic acid	
buffering chemicals	

The specific dye range evaluated was observed on January 2 and on May 11, 1976. The fabric being processed was a shirting material of 65% polyester/35% cotton and weighed 1.3 yards per pound. It was processed at a rate of 85 yards per minute. A combination of vat and dispersed dyes was used in the following procedure.

Process	Overflow Water (dm^3/s)	Observed Temperature (°C)
Dye pad at 60 C		
Dry	0	
Thermosol at 210-213 C		
Cool fabric	0.47 est	60
Chempad at 27 C	0	
Steam at 104 C	0.63	99 condensate
	0.63	38 water seal
Rinse at 49 C	0.75 (4 tubs)	43, 44, 54, 60
Oxidize at 54-60 C	0.06 (2 tubs)	70, 69
Soap at 88 C	0.12 2	89
Rinse at 77-82 C	0.75 (3 tubs)	71, 66, 66
Dry	0	

Figure 4 shows the wet processes of the dye range schematically. The cloth flow is indicated as well as the rinse, oxidation, and pH adjustment processes required. The oxidation baths were operating at higher temperatures and the final rinse at lower temperature than indicated as standard procedure.

Considerable variations in procedure exists from time to time to accommodate fabric styles and dye combinations. The department involved handles some ninety shades per week at about 30,000 yards per shade. The observations made in the following apply only to the particular conditions for the run cited, but some generality is expected to exist.

Discussion was initiated concerning the application of hyperfiltration or ultrafiltration to the existing process for the reclamation of chemicals. It was judged possible that some dye, sodium acetate, and detergent could be reclaimed. Most of the periodate is consumed in the process and is not reclaimable. It was judged probable that hot water could be reclaimed.

On the January 2 visit, the basic range operation was observed and samples of the drain were taken. On the May 11 visit, detailed data for energy calculations were taken together with the gathering of specific wastewater in drum samples for membrane screening tests at Clemson University.

A material balance (on the chemical additions reported by plant personnel) is given below:

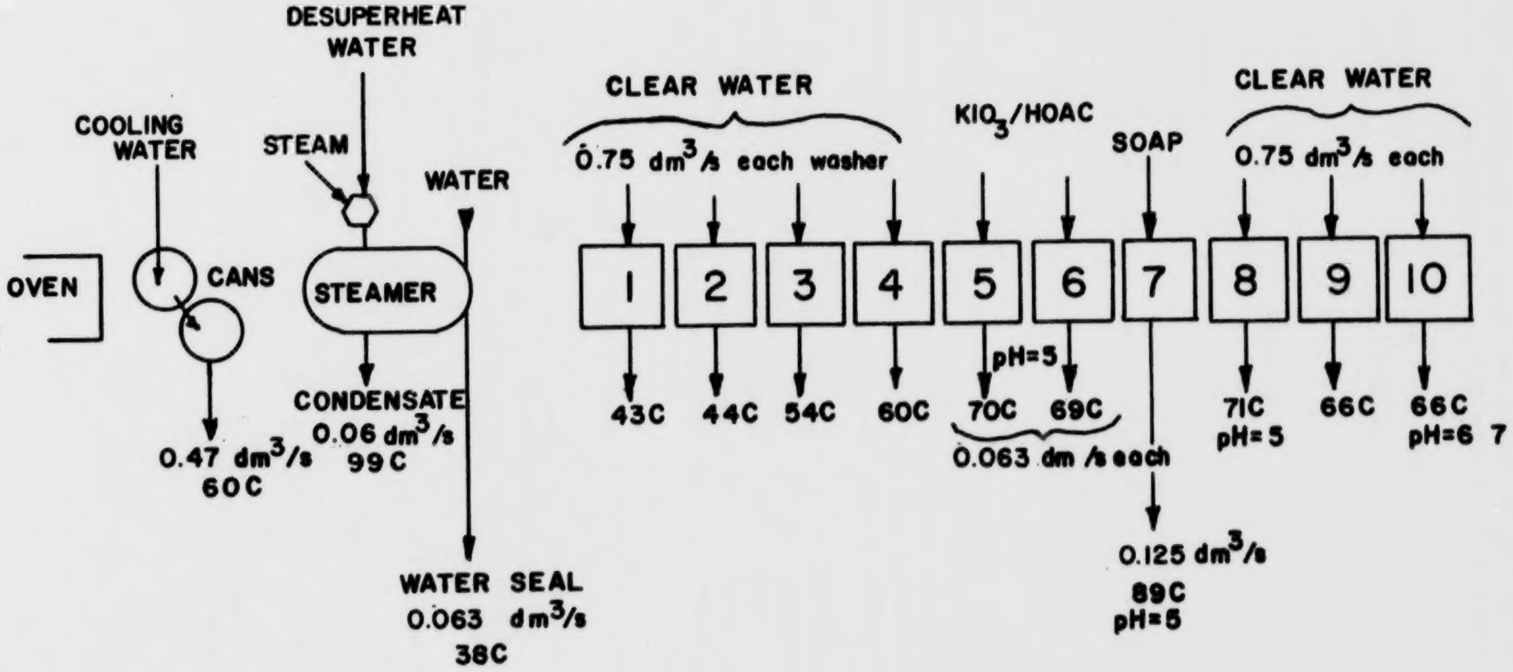
DESUPERHEAT WATER
COOLING WATER
STEAM
WATER
OVEN
CANS
STEAMER
0.47 dm³/s
60C
CONDENSATE
0.06 dm³/s
99C
WATER SEAL
0.063 dm³/s
38C
CLEAR WATER
0.75 dm³/s each washer
KIO3/HOAC
SOAP
CLEAR WATER
0.75 dm³/s each
1
2
3
4
5
6
7
8
9
10
43C
44C
54C
60C
pH=5
70C
69C
0.063 dm /s each
0.125 dm³/s
89C
pH=5
71C
pH=5
66C
66C
pH=6 7

FIGURE 4 SCHEMATIC DIAGRAM OF CONTINUOUS DYE RANGE PROCESS

Process	% O.W.B. Chemical Used[a]	Estimated % Active
Dye formulation for dye pad		
Vat dye mixture	8.30	2.0
Dispersed dye mixture	3.33	1.5
Antimigrant (sodium alginate)	2.30	0.2
Salt (NaCl)	0.73	100.0
Monosodium phosphate	0.25	40.0
Initial rinse, after steamer		
Tubs 1, 2, 3, 4 - no chemical added		
Chemical pad		
Sodium hydroxide (40% solution)	3.90	40.0
Sodium hydrosulfite	3.90	100.0
Oxidation bath - Tubs 5, 6		
Potassium iodate	0.25	100.0
Acetic acid (84% solution)	1.90	84.0
Final rinse bath		
Tub 7 - blended nonionic surfactant	0.73	
Tubs 8, 9, 10 - no chemical added, although pH buffering additives could be required		

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[a] The first column is the percent commercial chemical based on weight of bath (O.W.B.). The second column is the estimated actual chemical present. The remaining material is water or commercial diluents.

Samples of the effluent were removed from each overflow on the dye range on January 2 during which period the range operation was similar to that on May 11, 1976.

1.3.3 Energy and Water Usage

Energy losses by evaporation, radiation, and convection, and energy flow in the wastewater stream were examined.

The energy loss from the wash tubs by evaporation was calculated based on the data of Appendix A-5. As shown in Table 7, the evaporative heat loss from all wash tubs was calculated at 2.03 x 10^6 kJ/hr. The evaporative heat loss from the saturated moving cloth surfaces as it was transported from one tub to another was only about one-tenth of the total energy loss by evaporation. About 4.30 x 10^6 kJ/hr of energy was used to heat water from 18 C to process temperature and of this amount about 1.69 x 10^6 kJ/hr was recovered in the plant heat exchanger. The energy loss by radiation and convection was only about 15% of the energy loss by evaporation.

The total energy loss minus the recovered energy was found to be 4.93 x 10^6 kJ/hr. The use of energy was as follows: evaporative

TABLE 7. EVAPORATIVE LOSS ESTIMATE
(GJ/hr)

Wash Box	Standard Procedure (Temperature, C)	Evaporative Loss (GJ)	Observed Temperature (C)	Evaporative Loss (GJ/hr)
1	49	0.091	43	0.068
2	49	0.091	44	0.072
3	49	0.091	54	0.118
4	49	0.091	61	0.157
5	57	0.135	70	0.237
6	57	0.135	69	0.226
7	88	0.493	89	0.516
8	79	0.355	71	0.249
9	79	0.355	66	0.195
10	79	0.355	66	0.195
TOTAL		2.19		2.03

losses (30%), net to heat water (65%), radiation and convection included steamer (5%). These values are depicted graphically in Figure 5 and tabulated in Table 8.

TABLE 8. ENERGY CONSUMPTION FOR DYE RANGE

Energy Loss	
Evaporation	2.03 GJ/hr
To heat water	4.30 GJ/hr
Radiation and convection	1.38 GJ/hr
Steamer	1.62 GJ/hr
TOTAL	6.63 GJ/hr
Less energy recovered (from heat exchanger)	-1.69 GJ/hr
NET ENERGY SUPPLIED	4.93 GJ/hr

$$\text{Net energy consumption} = \frac{4.93 \times 10^6 \text{ kJ/hr (1 hr/60 min)}}{27.91 \text{ kg cloth/min}}$$

$$= 2944 \text{ KJ/kg cloth}$$

$$\text{Net water consumption} = \frac{0.416 \text{ m}^3\text{/min}}{27.89 \text{ kg/min}}$$

$$= 0.0174 \text{ m}^3\text{/kg cloth}$$

The above values are for the wet portions of the dye range. The entire range from the predryer through the dry can postdryer consumes an amount estimated as 7.94×10^6 kJ/hr in addition to the amounts already delineated. Thus, the wet processes only include approximately 40% of the total energy supplied to the range.

A detailed study on the energy consumption of the continuous dye range is included in Appendix D.

The water consumption was calculated to be 0.0074 m^3 per meter of cloth processed. The net energy was 2945.5 kJ/kg of cloth.

1.4 Pressure Becks

1.4.1 Process Description

Water and the dry cloth are charged to the beck in sequence. The temperature of the beck is raised gradually by adding steam though its heat exchanger. At a certain temperature chemicals are added to the process to effect the dyeing. The dyeing is done in a two-step operation. The first step is to raise the temperature to an elevated level allowing the dispersed dye to penetrate the polyester fiber. As soon as that dye

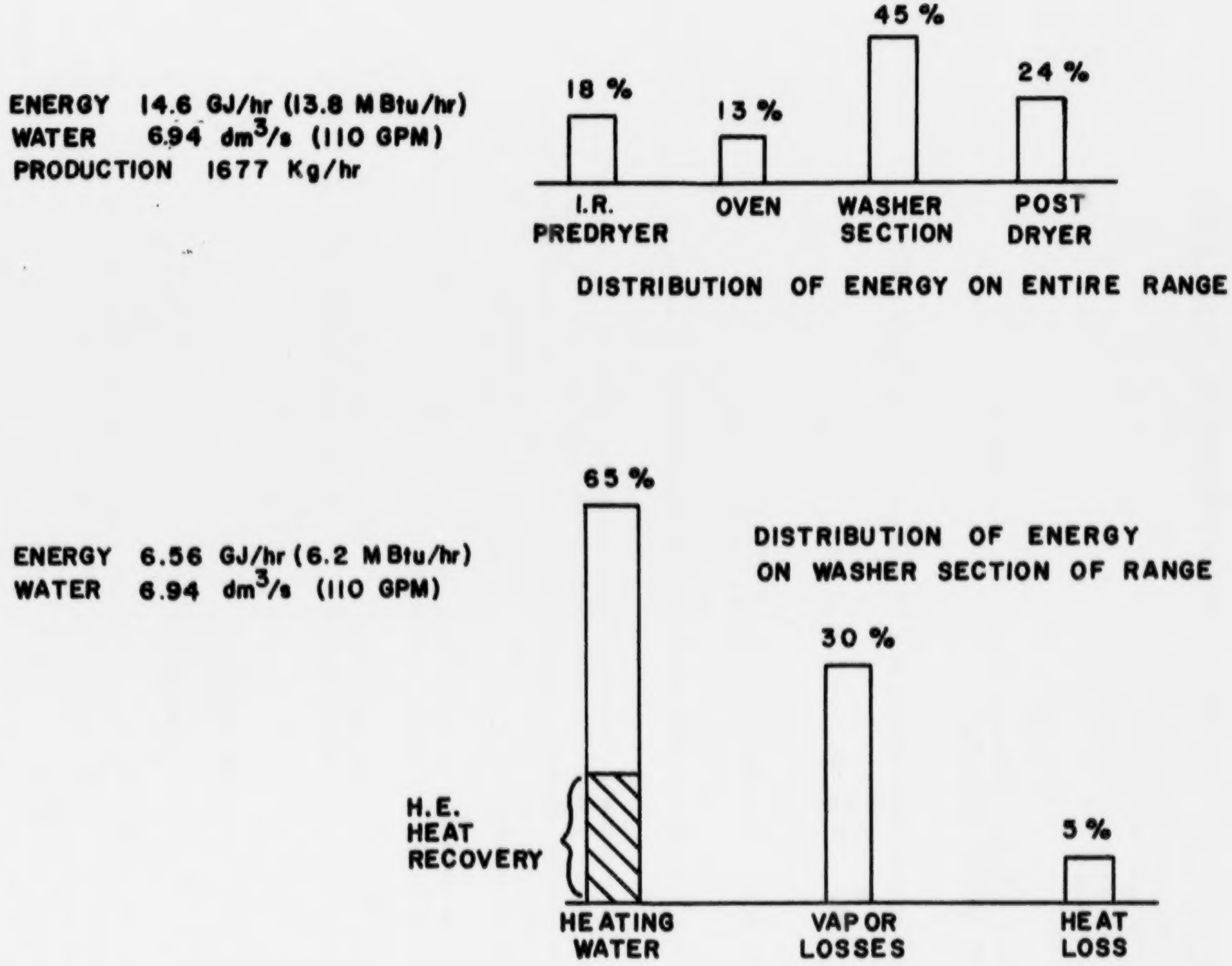

FIGURE 5 ENERGY DISPOSITION ON CONTINUOUS DYE RANGE

has penetrated the cloth sufficiently a patch test can be made validating its performance. Then the temperature is adjusted to a new, usually lower level for a certain time to accomplish the direct dyeing of the cotton. Following the dyeing the beck is rinsed with fresh water, the fluid is dropped, more water is added, the rinse is again accomplished, and the cloth then is removed.

1.4.2 Chemicals Used

Chemicals used are a combination of dispersed and direct dyes, salt, and other dyeing auxiliaries.

1.4.3 Energy and Water Consumption

Pressure becks were also studied to determine the energy lost by evaporation, convection, and radiation during the dye cycle and to determine the energy associated with heating water in the beck. The observed dye cycles for these becks are given in Figure 6 (low-pressure) and Figure 7 (high-pressure).

The low-pressure beck cycle studied involved the dyeing of 3175 meters of material weighing 1280 kg. The water requirement to fill the beck at the start of the cycle was 13.63 m^3 at a temperature of 18 C. During the dyeing cycle there were three periods of heating before the actual dyeing took place. Initially the water was heated to 52 C, the cloth and a chemical charge added. The temperature was then elevated from 52 to 85 C, the pH of the fluid was adjusted, and a final temperature adjustment to 104 C was made. The actual dyeing took place after the beck contents were heated to 104 C. The beck door was open at times during the cycle to load and unload the cloth, to add chemicals to adjust the pH, and to check the cloth for proper color (patch test). At these times, vapor allowed to escape from the vent amounted to a heat loss of 0.79×10^6 kJ. Convection and radiation losses were calculated using an overall average heat transfer coefficient of 11.3 W/m^2-K. The heat transfer in this particular case by radiation and convection was determined to be only 7% of the total heat losses. The total energy requirement for the low-pressure beck was calculated to be 4787 kJ/kg of cloth. The water consumption was 81.76 m^3 or 0.074 m^3/kg of cloth. These consumption rates were lower than comparable rates obtained for atmospheric becks, due to lower liquor ratio and the reduced evaporation from the closed beck. As shown in Figure 8, approximately 80% of the total energy was used to heat water.

The high-pressure beck dyeing cycle involved 877 kg of cloth. The beck was filled with 10.6 m^3 of water at the start of the cycle

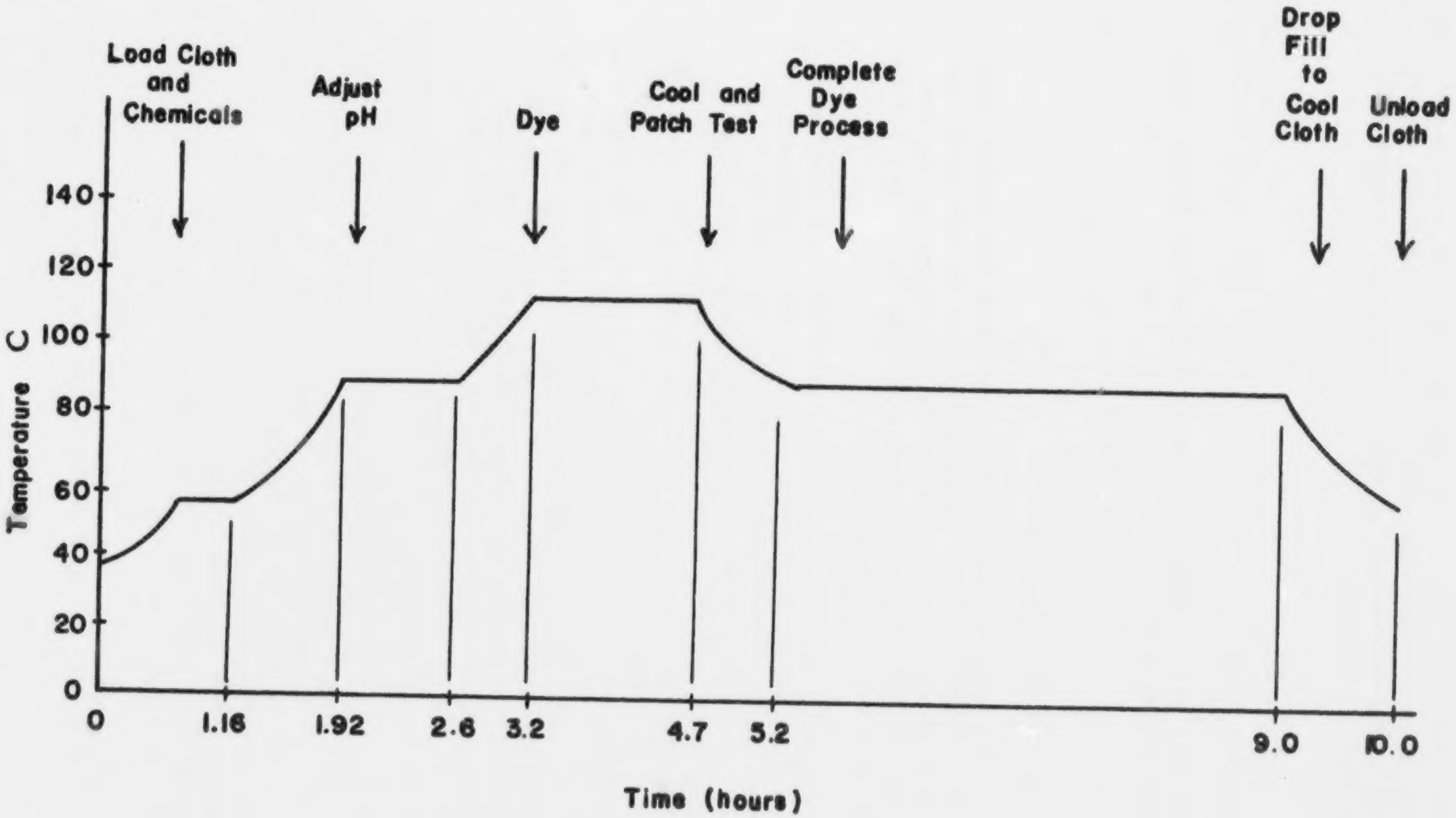

FIGURE 6 CYCLE PROCEDURES FOR LOW PRESSURE BECK

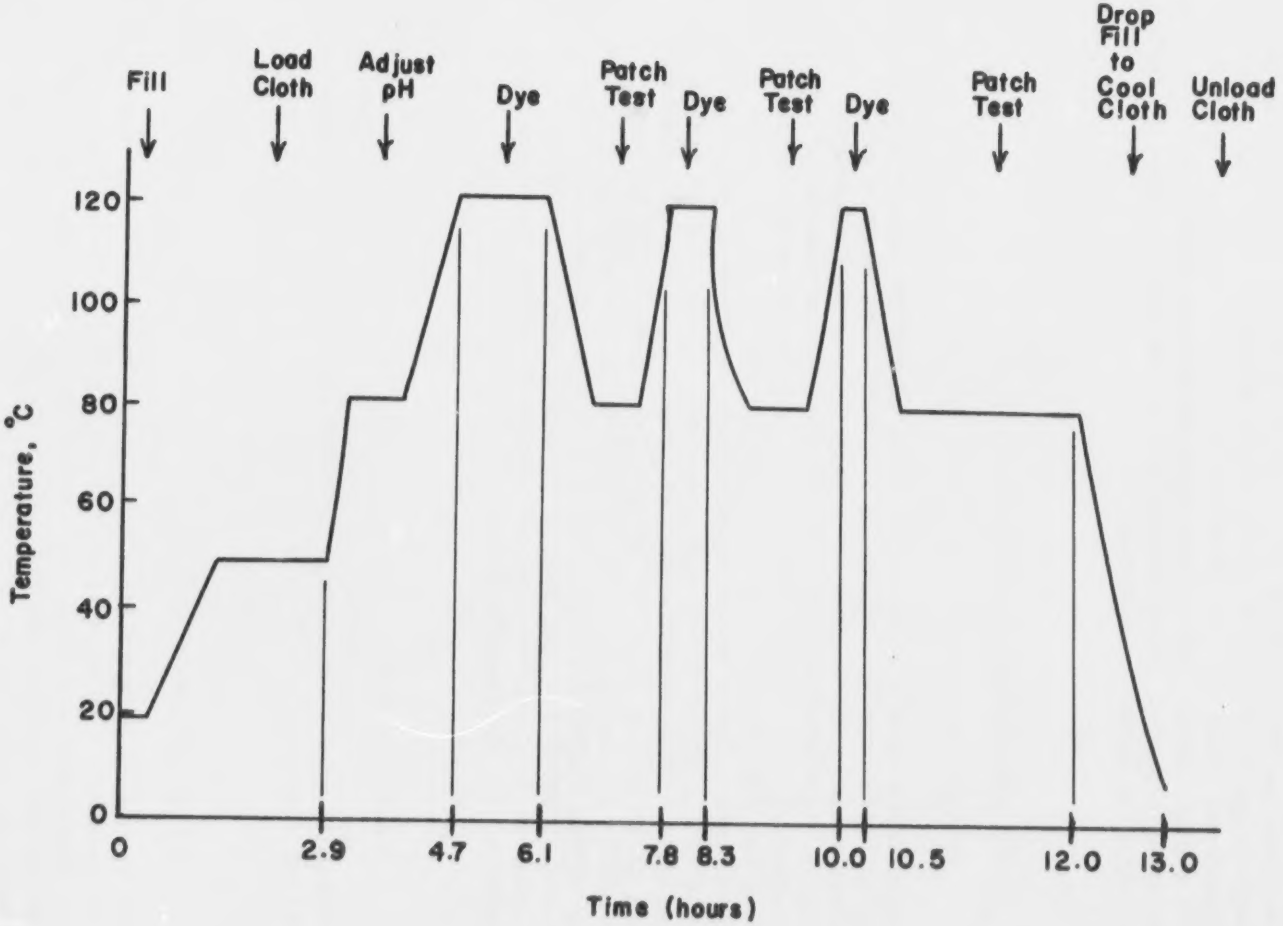

FIGURE 7 CYCLE PROCEDURES FOR HIGH PRESSURE BECK

at a temperature of 18 C. The dyeing was performed during three periods, each at 121 C a higher temperature than for the low-pressure beck. All energy calculations were performed in the same manner as for the low-pressure beck. The total energy required to heat the water and replace that lost by evaporation, convection, and radiation was nearly 10.11 x 10^6 kJ, or 11530 kJ/kg of cloth. The total water requirement was 69.65 m^3, and amounted to a water consumption of 0.092 m^3/kg of cloth. Again, the consumption rates were lower than obtained for atmospheric becks. Also, nearly 80% of the total energy is used to heat water as shown in Figure 8.

1.5 Continuous Rope Preparation Range

1.5.1 Process Description

Cloth comes from a storage pit where it may be treated with enzymes to break down the starch in the starch/PVA mixture of sizing materials. Cloth comes in a rope form to the alternator where it is circulated at high temperature for the removal of the sizing material. It then is fed into a caustic saturator which basically exposes the cloth to 0.4% caustic solution. It flows from there into a J-box where it is exposed by steam at 99 C for about one hour. It is drawn from the J-box into a caustic washer and then goes into a second washer at lower temperature to further wash the cloth of its dissolved materials. Then the cloth goes to a peroxide saturator where it is exposed to a bleaching solution, wetting agent, peroxide bleach, and a mild caustic addition. It is allowed to steam for one hour at 99 C and then is rinsed in clear water at 71 C and in a second washer at 27 C. The cloth is then prepared for further finishing.

1.5.2 Chemicals Used

Chemicals used on the range are mild caustic solutions, bleach, and wetting agents.

1.5.3 Energy and Water Consumption

The rope-form preparation range studied had process elements shown in Figure 9. In this range the alternator performs the desizing operation, and there is a saturator, J-box, and washer combination for both the caustic and bleaching sections. Water from washer #4 forms the entire water flow for washer #2. Flows and temperatures of the drains are indicated by Figure 9. The energy calculation methodology was similar to that of the open-width range. Vapor loss from the enclosed washers was assumed

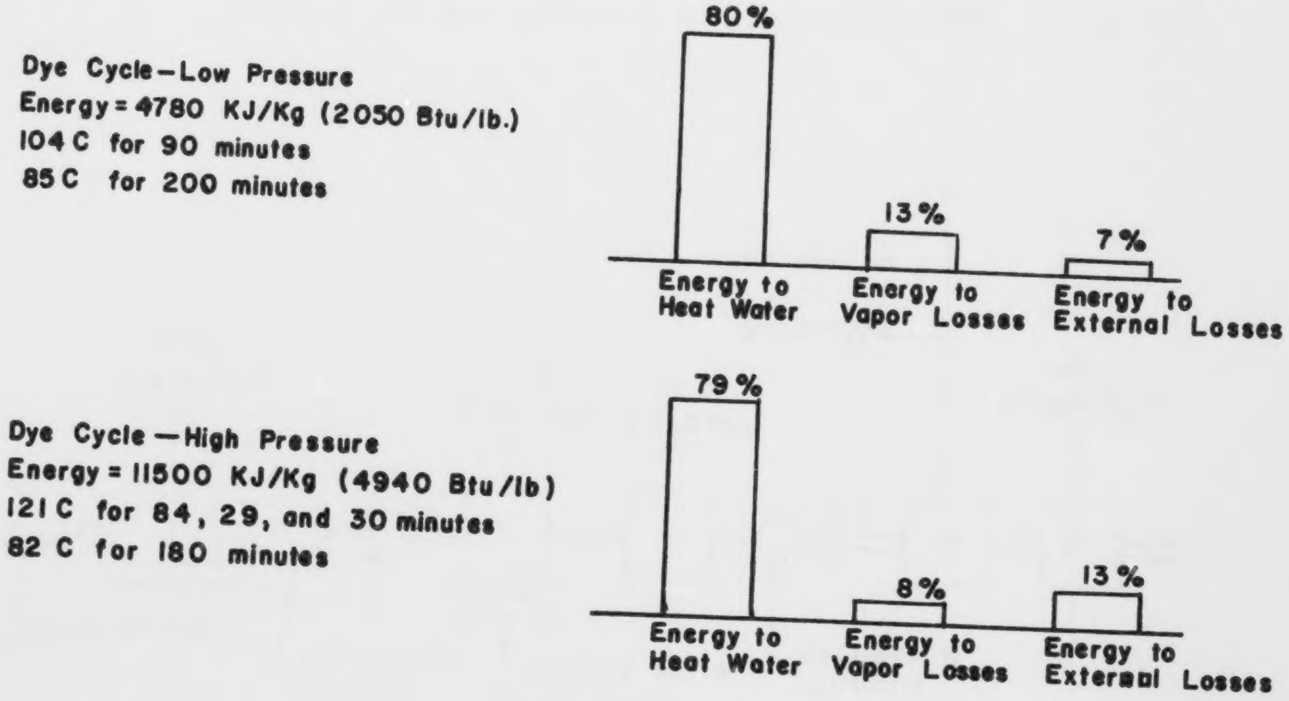

FIGURE 8 ENERGY CONSUMPTION FOR PRESSURE BECKS

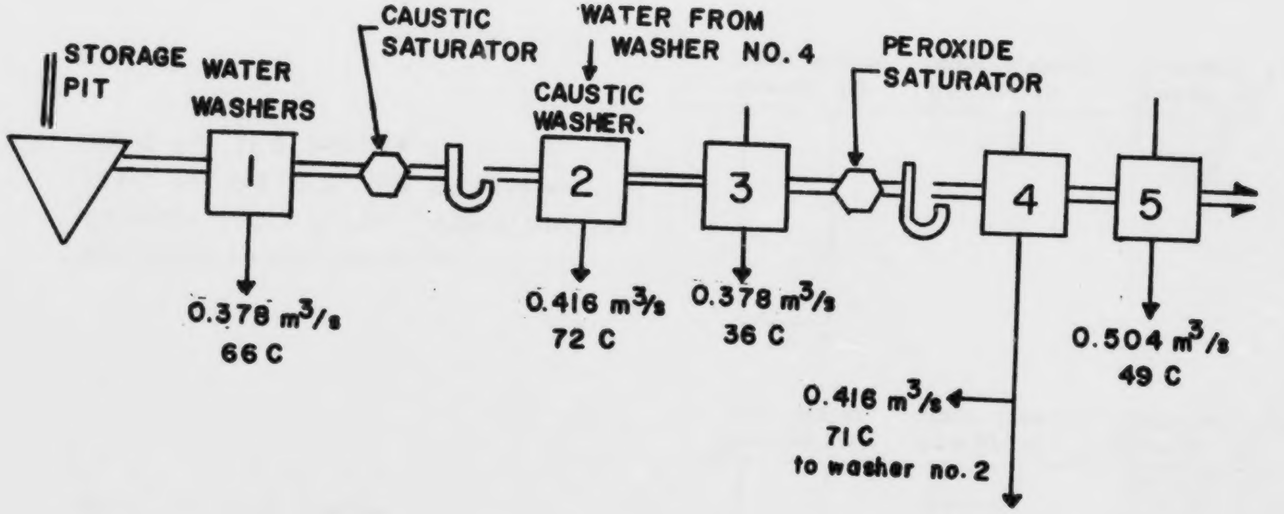
STORAGE PIT
WATER WASHERS
CAUSTIC SATURATOR
WATER FROM WASHER NO. 4
CAUSTIC WASHER.
PEROXIDE SATURATOR
1
2
3
4
5
0.378 m3/s 66 C
0.416 m3/s 72 C
0.378 m3/s 36 C
0.416 m3/s 71 C to washer no. 2
0.504 m3/s 49 C

FIGURE 9 SCHEMATIC DIAGRAM OF ROPE PREPARATION RANGE

negligible, and the loss rate per unit area of the rope-form cloth was taken to be equivalent to that in the atmospheric beck observations. The physical envelope of the rope was estimated for an area basis. The steam rate to the J-box was taken from plant-supplied data, but the value reported is much higher than expected based on calculated estimates.

The entire system energy use required to operate the range was calculated as 13.0 x 10^6 kJ/hr. The production rate was 174 m per minute of cloth having 3.47 m/kg, yielding 3007 kg per hour of production. The energy use per unit of production was therefore 4341 kJ/kg. Figure 10 shows the distribution of energy on the range by category. As previously mentioned, the J-box may actually require a much smaller amount than indicated. In any event, the heating of water required at least 76% of the total energy required for the rope range.

The mill design provides for the collection of hot drain water to allow heat exchange with incoming water. Other sources of "waste" energy are also used to elevate the average inflow temperature such that two-thirds of the energy required to heat water is supplied by energy recycle. This fractional energy recovery is indicated in Figure 10 by shading. Only a portion of the energy recovery originates at the particular range, and the portion is not readily determined.

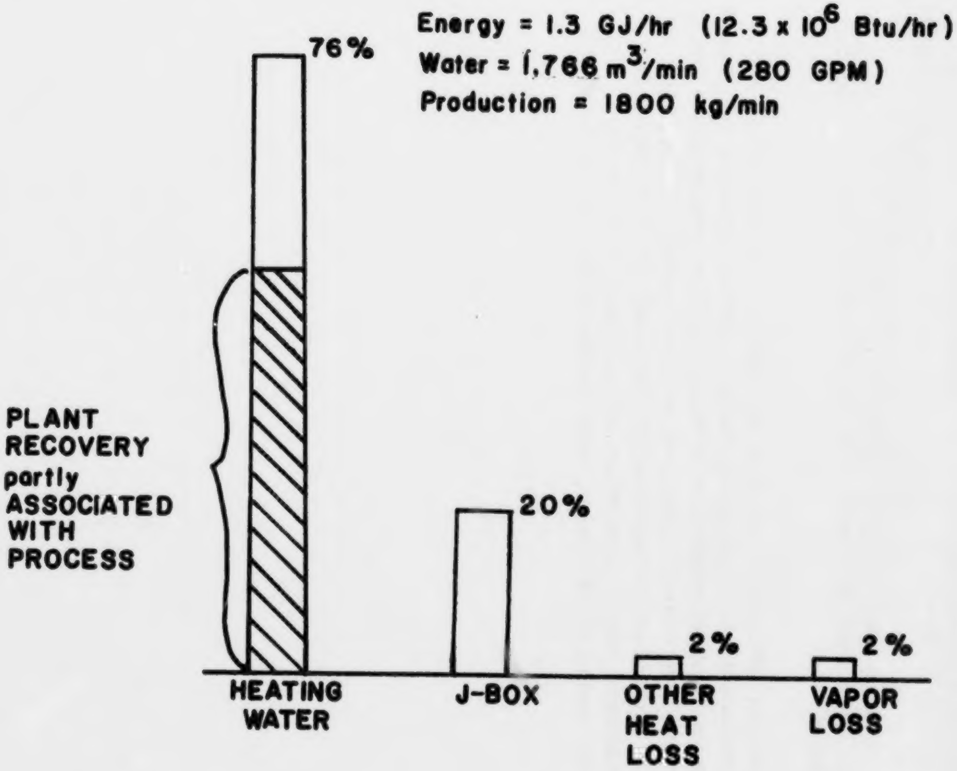

FIGURE 10 DISTRIBUTION OF ENERGY ON ROPE PREPARATION RANGE

2.0 CHARACTERIZATION OF WASTEWATER DISCHARGES

2.1 Atmospheric Beck

The analyses of several process wastewater samples taken directly from the atmospheric dye bath are presented in Tables 9 and 10. The highest concentrations of chemicals are present in the dye baths, as shown by the total solids analyses (8253, 5701, 6378, and 9200 mg/ℓ). These solids are 90% salt, which is used to cause the dye to adhere to the fiber. The salt may be concentrated by hyperfiltration but not by ultrafiltration. The remaining 10% of the solids are organic additives, such as dispersing agents and dyes, which also may be concentrated by hyperfiltration but less so or not at all by ultrafiltration membranes.

2.2 Pressure Beck

The analyses of process wastewater samples taken from the pressure beck on November 3, 1975, is presented in Table 11. These data show very high concentrations of salt being discharged by the high- and low-pressure becks. It seems that the salt, which is over 2% concentration, is valuable if suitably processed by high-temperature hyperfiltration membranes.

2.3 Open-width Preparation Range

Water taken from the various drains of the continuous preparation range on November 3, 1975, and March 2, 1976, was analyzed as shown in Table 12. Analysis of the cloth for material removal was conducted as shown in Appendix E. Calculations using measured flow rates showed reasonable comparisons of "removal from cloth" and "addition to water." Appendix E also shows a breakdown of the relative constituents of the sizing formulation as removed. The drains from the alternator, desize washer, and caustic washer show large organic loading as is expected.

2.4 Continuous Dye Range

The continuous dye range (see Figure 4) was sampled and each drain analyzed as reported in Table 13. The first four boxes show

TABLE 9. ANALYSIS OF SAMPLES - ATMOSPHERIC BECK

Identification	COD	TOC	Color	Total Solids	Suspended Solids	Methylene Blue Active Surfactants	Chromium	Copper	pH
#1 Fix, Lot 6199 10/31/75	98	22	133	557	10	0.34	0.003	0.042	6.40
#1 Dye, Lot 6199, 10/31/75	400	121	1540	298	54	3.50	0.006	0.250	6.95
#2 Fix, Lot 6159 10/31/75	605	173	224	3194	22	<0.10	0.002	0.042	6.80
#2 Dye, Lot 6159 10/31/75	2176	441	98	8253	18	<0.10	0.001	0.025	7.00
Beck #4, Dye Fix #6186, 10/31/75	88	21	63	830	18	<0.10	0.005	0.008	6.95
Beck #4, Dye 6186 10/31/75	3182	396	602	5701	43	<0.10	0.011	0.058	8.40
Beck #15, Dye 5685 10/31/75	996	159	154	6378	44	1.90	0.001	0.058	5.45
Fix #15, 5685, 10/31/75	224	66	42	300	9	0.08	0.001	0.042	4.30
Dye #16, L 94896 10/31/75	512	151	6272	948	640	29.00	0.006	0.025	7.50
Beck #18, Dye 6052 10/31/75	1610	191	455	9200	35	0.26	0.003	0.033	7.60

[a] All results are reported in mg/ℓ, except pH (unitless) and color (ADMI).

TABLE 10. ANALYSIS OF SAMPLES - ATMOSPHERIC BECK

Identification	COD	TOC	Color	Total Solids	Suspended Solids	Methylene Blue Active Surfactants	Chromium	Copper	pH
Beck #21, Dye Fix Lot 292, 10/31/75	49	41	77	876	11	<0.10	0.005	0.033	7.2
Scour Dump #3, 9/15/75	270	158	168	302	8	<0.10	0.002	0.021	6.6
Overflow Dye #38, 9/15/75	530	196	532	4494	24	<0.10	0.002	0.379	6.1
Dye to drain #38	56	69	350	148	10	<0.10	0.006	0.053	6.8
Scour #3	614	300	658	642	92	<0.10	0.006	0.016	6.7
Dye Start Overflow #38, 9/15/75	1033	338	1043	9376	40	<0.10	0.001	0.293	5.8
Scour Overflow #3, 9/15/75	1098	455	938	1150	154	<0.10	0.007	0.053	7.3
Scour Solution, Beck #4, Lot 6279, 11/5/75	1740	597	490	1806	40	<0.10	0.004	0.053	10.1
Scour Solution, Beck #6, Lot 6274, 11/5/75	609	324	210	1005	4	<0.15	0.005	0.011	10.4
Scour Solution, Beck #15, Lot 6269, 11/11/75	1795	701	266	1252	66	<0.23	0.019	0.032	7.0

[a] All results are reported in mg/ℓ, except pH (unitless) and color (ADMI).

TABLE 11. ANALYSIS OF SAMPLES - PRESSURE BECKS

Identification	COD	TOC	Color	Total Solids	Suspended Solids	Methylene Blue Active Surfactants	Chromium	Copper	pH
High-pressure beck 85°F just before drainage, 11/3/75	2821	346	1337	21958	72	5.3	0.022	0.085	6.4
Low-pressure beck 180°F end of dye time, 11/3/75	558	93	371	6294	28	-	0.055	0.133	6.55
Low-pressure beck, 115°F just before emptying, 11/3/75	3221	344	763	26758	43	-	0.067	0.155	7.6

[a] All results are reported in mg/ℓ, except pH (unitless) and color (ADMI).

TABLE 12. ANALYSIS OF SAMPLES - OPEN WIDTH PREPARATION RANGE

Identification	COD	TOC	Color	Total Solids	Suspended Solids	Methylene Blue Active Surfactants	Chromium	Copper	pH
Continuous range caustic washer 11/3/75	7954	4260	1344	4014	74	1.4	0.033	0.075	12.2
Continuous range desize washer 11/3/75	8336	3846	658	8578	404	1.2	0.022	0.219	6.4
Continuous range GC alternator washer 11/3/75	1405	611	644	1630	314	0.3	0.055	0.171	6.3
Continuous range peroxide washer, 11/3/75	3452	1753	630	3948	100	-	0.044	0.200	11.0
Alternator rinse, 3/2/76	4160	-	-	2930	270	0.02	-	-	6.2
Caustic desize, 3/2/76	22200	-	-	17625	2680	0.04	-	-	12.45

[a] All results are reported in mg/ℓ, except pH (unitless) and color (ADMI).

TABLE 13. ANALYSIS OF SAMPLES - CONTINUOUS DYE RANGE

Analyses[a]	Tub #1	Tub #2	Tub #3	Tub #4	Tub #5	Tub #6	Tub #7	Tub #8	Tub #9	Tub #10
pH	12.4	11.8	11.7	11.5	4.4	4.5	4.5	4.3	3.7	3.8
BOD	140	25	35	20	0	0	0	0	50	50
COD	240	240	200	740	0	0	0	620	500	500
Total Solids	4086	1306	1187	816	4035	5085	3934	992	282	100
Suspended Solids	46	10	16	22	132	198	228	18	12	16
Color	3840	880	1000	2480	840	1640	2835	640	35	25
Specific Conductance	5500	2300	2000	1200	1800	2300	2000	800	500	400
Chromium	0.030	0.280	0.080	0.125	0.125	0.155	0.030	0.125	0.060	0.060
Copper	0.070	0.040	0.075	1.15	1.55	4.30	3.60	0.50	0.10	0.15

[a] Results are in mg/ℓ, except for pH (unitless), color (APHA units), and specific conductance (micromhos/cm).

the washout following the chemical addition on the range. Total solids diminish from box #1 through box #4. The pH gradually diminishes from a high value down toward a pH of 11. COD is fairly low compared to the amount of total solids in the stream and the color first diminishes and then rises as the temperature of the bath is escalated forcing more and more of the colored material from the cloth. In tubs #5 and #6 potassium periodate is added with acetic acid to oxidize the dye and also prepare the cloth for final finishing and resin finishing. In tub #7 soap is added to clean the cloth of dispersed material and the washout in tubs #8, #9, and #10 is shown to be effective in reducing total solids even though the water is down to about the 100 mg/ℓ level. Boxes #5, #6, and #7 have very minimal overflow contributing only slightly to the total loading from the continuous dye range.

2.5 Rope Preparation Range

The rope preparation range (Figure 9) was sampled and the analysis is reported in Table 14. The first box shows evidence of a large organic loading corresponding to the size removal in the first box. Conductance is fairly low indicating the amount of ionics is low and the suspended solids is a relatively large value probably indicating large amounts of cotton fiber being added to the bath. The results for the second and third wash box (following the caustic step) also indicate considerable organic loading. Wash box #4 which follows the peroxide saturator has much less loading of all constituents than the earlier boxes.

TABLE 14. ANALYSES OF DRAINS IN ROPE PREPARATION RANGE

Parameter[a]	Wash Box #1	Wash Box #2	Wash Box #3	Wash Box #4
Sample Number	1067	1068	1074	1078
Conductance	896	5400	1080	585
pH	4.0	10.9	9.0	8.3
Phenol Alkalinity	0	925	16	0
Total Alkalinity	107	2400	547	288
Total Solids	7695	10438	1769	1007
Suspended Solids	3320	1360	266	169
COD	27520	9880	2293	656
Residual Chlorine	0	too colored	0	0

[a] All results are in mg/ℓ, except conductance (micromhos/cm and pH (unitless).

3.0 POSSIBLE PROCESS MODIFICATIONS

It is recognized that certain process modifications may be required to allow incorporation of hyperfiltration. Other methods are foreseen which aid the economic benefits by allowing lower cost installations or more complete chemical reuse.

3.1 Atmospheric Dyeing

Closed-cycle or substantial permeate reuse will result in there being no cold water for the beck processes. This causes a number of perhaps small changes in the procedure normally used in atmospheric dyeing. The only water available to fill the beck to begin scour is hot whereas at present it is cold. The rinse that is conducted at the end of the scour process will be hot water rinse rather than cold water rinse. The water available for filling the beck prior to dyeing will be hot. The dye and all of the auxiliaries will be added to cloth and water which is already hot rather than at present adding the dye and auxiliaries cold and raising the temperature gradually. Again, the rinse will be conducted with hot water rather than with cold as it is at present. There are several problems, some mechanical and some having to do with the relative application of the materials. It must be determined that the cloth can withstand high-temperature rinses and that if any draining is to be done at the hot condition that the cloth will not be harmed by dropping the fluid in preparation for the step while the cloth is hot. The dye certainly must be carefully added to the bath so that application of dyestuff is uniform on the cloth to prevent streaking and diminish end-to-end variations. It is anticipated that the procedure can be used with direct dyes with some difficulty. Because of the anticipated difficulty a full-scale evaluation was conducted and is reported in a later section. The evaluation resulted in a satisfactory dyeing so that the application of the dye to hot solution is a reasonable assumption. Some of the side benefits of having only hot water available, including that for rinsing, is that the rinsing may be more effective, allowing the dyeing to be done in a shorter period resulting in a greater productivity of the unit. If hot water processing is done at a faster rate the fraction of energy which goes to evaporation loss will be diminished also resulting in a comparative energy saving.

Salt in dyeing is used to force the dye to the cloth. Typical direct dye exhaustions show 70% without salt and 90% with salt. By using a higher concentration of dye in the dyebath, the direct dyeing operation may be performed with no salt at a cost savings. Since the dye may be recovered and concentrated by the hyperfiltration unit, no dye is wasted. It is possible that the dye can be concentrated further if the relatively large salt content is not used due to elimination of the large osmotic pressure resistance which could otherwise be expected. The procedure should speed up production by shortening the dye cycle.

Modifications are possible which will contribute to a decreased volume flow of water. The rinsing procedures can be improved by adopting a drop/fill rather than a rinse overflow operation. A critical standard for sufficiency of rinsing is badly needed. By careful minimization of the water flows the cost of a hyperfiltration unit will be proportionately reduced.

3.2 Continuous Dye Range

The conventional continuous dye range in the textile industry today uses dispersed dyes for polyester fibers and vat or reactive dyes for cotton or rayon fibers. This applies to blended fabrics and much of the 100% cotton fabrics which are currently processed. Since these dyes leave little usable residue in the rinse solutions, dye recovery is not practical. The streams examined for recovery were the rinsing or scouring baths which follow immediately after the fixation of the dye in the steamer. Hot rinse water, detergents, and acetate convertible to acetic acid can be recovered. A recovery scheme using a modified process is shown in Figure 11.

The application of an ultrafiltration membrane to the rinsing baths after the steamer will allow water to be recovered and conserve acetic acid in the oxidation tubs (#5 and #6). It is also possible to recover detergents and hot water from tubs #8, #9, and #10 with a hyperfiltration membrane, or hot water with an ultrafiltration membrane.

As the analyses of water samples taken from the different tubs in the dye range show, the highest concentration of chemicals in the rinse tubs (#1, #2, #3, #4, #8, #9, and #10) is 0.5% solids. It is projected that the solids in Tubs #1, #2, #3, and #4 may build up to 6000 to 12,000 mg/ℓ in a recycle system such as that shown in Figure 11. This higher solids level would be of value in tubs #1 and #2 in preventing washdown of the vat dye before it is oxidized.

The countercurrent flow shown in tubs #8, #9, and #10 should facilitate the buffering of the fabric to pH 4-6, required for resin finishing. The buffer could be regenerated with mineral acid as it is recycled.

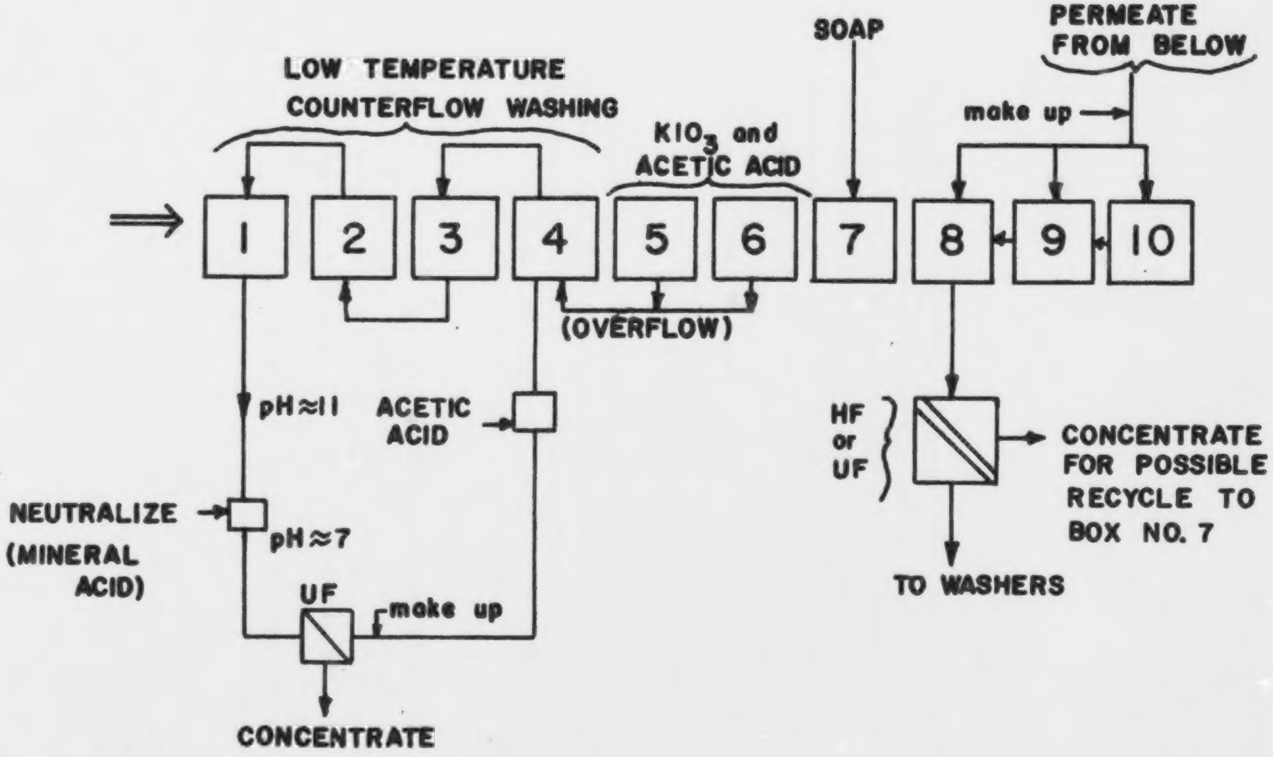
LOW TEMPERATURE COUNTERFLOW WASHING
KIO_3 and ACETIC ACID
SOAP
PERMEATE FROM BELOW
make up
1
2
3
4
5
6
7
8
9
10
(OVERFLOW)
pH≈11
ACETIC ACID
NEUTRALIZE (MINERAL ACID)
pH≈7
UF
make up
CONCENTRATE
HF or UF
CONCENTRATE FOR POSSIBLE RECYCLE TO BOX NO. 7
TO WASHERS

FIGURE 11 IMPLEMENTATION OF PROCESS MODIFICATIONS FOR APPLICATION TO DYE RANGE

3.3 Continuous Rope Preparation Range

The best place for process modifications appears to be the scouring operation. If 1-5% solvent (varsol-type) can be used with the scour solution it should replace some of the alkali used and effectively removed waxes to give a well-scoured fabric. This would decrease the alkali consumption and make the waste more suitable for water recovery by commercial membranes. The alkali load on the waste treatment system would also be reduced.

The membranes presently available do not provide any significant concentration capability for caustic. However with a saturator source at 6% NaOH, the wash water approaches 0.4% NaOH when it enters in a neutral condition. If 0.4% NaOH water were used for washing, the effluent would approximately double in concentration. An exponential type rise would continue until an equilibrium condition is reached. At equilibrium, the caustic removed in the washers will be concentrated as if in the makeup flow alone. Thus the level of caustic in untreated, recycled wash water will rise despite the fact that the membrane does not specifically separate it.

The above leads to the process modification shown in Figure 12. The (assumed four) washers will be operated in counterflow with the membrane applied to the effluent. The concentrate containing waxes and trash removed from the cloth will be routed to waste treatment. The permeate, now highly caustic, will be divided into a stream for recycle and a stream for caustic recovery by evaporation. Makeup fluid will be added to the last washer section in an amount which will preclude detrimental effects of excess caustic in the bleach section. It may be possible to reduce the caustic addition to the bleach saturator. The savings would include (a) water and energy of recycled permeate, (b) a reduction in the purchase of caustic in the amount of that recovered from permeate, (c) perhaps less caustic addition in the peroxide saturator, and (d) lower cost of waste treatment both by reduction of neutralizing acid and by a decrease in the volume of total waste.

3.4 Pressure Beck Dyeing

Many of the statements from the atmospheric beck dyeing section are applicable to the pressure beck. Some cooling of the beck water will be necessary to preclude the tendency of all reuse water to assume the highest process temperature. The degree of cooling is not expected to be substantially different from that in present practice.

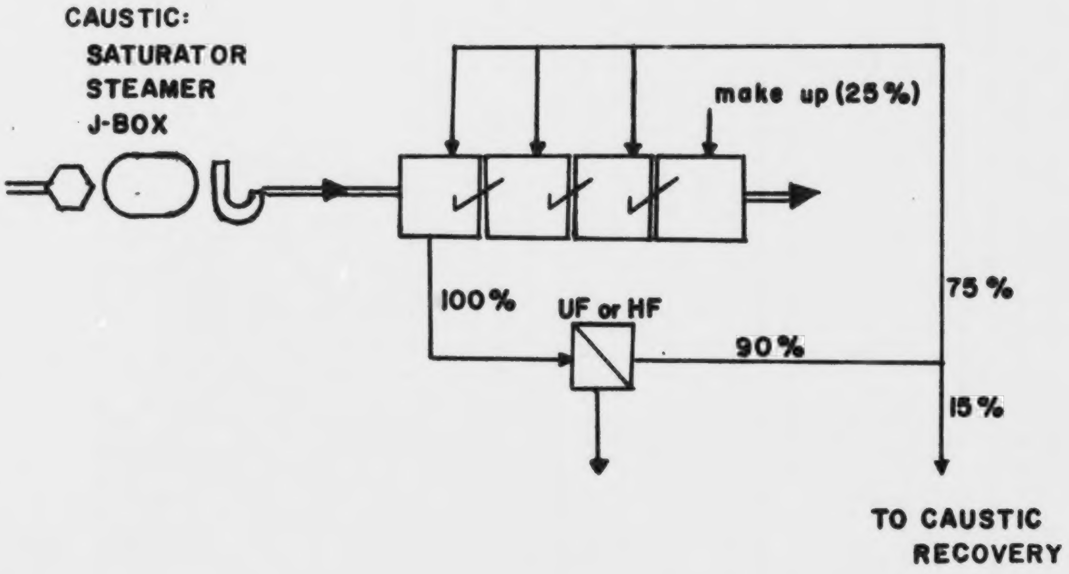
CAUSTIC:
SATURATOR
STEAMER
J-BOX
make up (25%)
100%
UF or HF
90%
75%
15%
TO CAUSTIC RECOVERY

FIGURE 12 CAUSTIC WASHER SECTION PROCESS MODIFICATION

3.5 Open-width Preparation Range

The open-width range surveyed is provided with plumbing to allow recycle of water from the bleach washers to the upstream desize washer, but this recycle is not always maintained. It is considered possible that a water savings may be effected through the use of higher operating temperature. A full-scale demonstration of this concept is included in a later section. The use of a solvent for scouring may allow the same advantages as on the rope-form range.

4.0 ENERGY SAVINGS POTENTIAL THROUGH RECYCLE

The dyeing and finishing of textile products is a process which consumes a considerable amount of industrial water. The effluent water from these processes contains residual chemicals and energy which may warrant recovery on a purely economic basis in addition to the resultant benefits of environmental protection and energy conservation. This report segment presents the details of an energy and chemical balance on selected piece dyeing processes which represent current practice for this class of batch process. The authors realize that considerable variations in procedure exist among the plants; nonetheless, the results are presented in the hope of reasonably general applicability and to explain a method for evaluating such a paucity of field data.

4.1 Atmospheric Beck

The energy use has been reported in Section 1.1.3 and Appendix C. Discussions of process modifications are found in Section 3.1. Here it is assumed that rinsing may be performed with hot water, that the fluid may be "dropped" at temperatures up to 75 C, and that chemicals and dye may be administered at any temperature. The permeate from the dye and scour operations may be used indiscriminately, but the fixing fluid permeate must be segregated. It is further assumed that the various baths may be drop/fill diluted in contrast with the present overflow rinse.

In addition to the assumptions stated concerning feasible operations the following estimates of a numerical nature are assumed. On the average, four beck volumes are used to rinse after each process, the last volume being the "fill" fluid for the next process. The cloth will retain 5% of one beck volume when the fluid is drained. The practical limit is expected to approximate a 75% fluid drop. All measures for energy recovery apply only to energy used for heating water (about one-half the total) and the remaining half is not subject to recycle by any water based process, including hyperfiltration.

4.1.1 Energy Recovery by Plant-scale Heat Exchangers

As mentioned in the assessment of energy balance for the processes, the outflowing water in every case has been warmed considerably.

One method of energy recovery is to operate a heat exchanger with the outflow water heating the inflow water on a plant scale. Some incoming water leaves the dye plant on the cloth enroute to the dryer while condensing steam usually adds a similar amount during the water heating mode. Therefore the hot and cold flows are approximately equal. For such a case in a counterflow (or equivalently a multiplass crossflow) heat exchanger, the temperature loss in one fluid equals the gain in the other. All of the fluid entering the plant, including rinse water, is elevated in temperature so that the outflow temperature will rise when energy is recycled in this manner. Let ΔT represent the rise in temperature as the fluid passes through the plant. This elevation in temperature results from one volume of fluid each at 74 C, 96 C, and 49 C (as shown in Figure 2), diluted with N (taken as 3) volumes of rinse water at T_I, or in equation form conservation energy yields

$$\Delta T\ (N + 1) \times 3 = (74 - T_I) + (96 - T_I) + (49 - T_I). \qquad (1)$$

When $T_I = T_s$, the process entering temperature (T_I) equals the incoming fluid temperature (T_s). A value of $T_I = T_s = 18$ C, and $N = 3$ results in $\Delta T = \Delta T_s = 13.75$. When a heat exchanger of effectiveness E is used, the outflowing hot fluid temperature will be $\Delta T + T_I$, and the definition of E

$$\frac{T_I - T_s}{T_I + \Delta T - T_s} = E \qquad (2)$$

allows computation of T_I from equation (1) as

$$T_I = \frac{T_s\ (1 - E)\ (N + 1)}{N + 1 - NE} + \frac{(74 + 96 + 49)\ E}{3(N + 1 - NE)} \qquad (3)$$

Strictly speaking this equation applies only up to $T_I = 49$ C at which point it implies that the water would be cooled to perform the dye fixing at 49 C. The energy saved is that fraction not used to heat the water from T_s to T_I or

$$\text{Fraction saved} = \frac{3\ (T_I - T_s)}{(74 - T_s) + (96 - T_s) + (49 - T_s)}\ . \qquad (4)$$

Figure 13 shows the fractional savings as a function of the exchanger effectiveness E. Present economics are such that this type heat exchanger may be purchased for a cost of the order of a year's energy savings. However, some fluids are not amenable to cooling due to high fouling or congealing. Also no chemical or water reuse is available using heat exchangers.

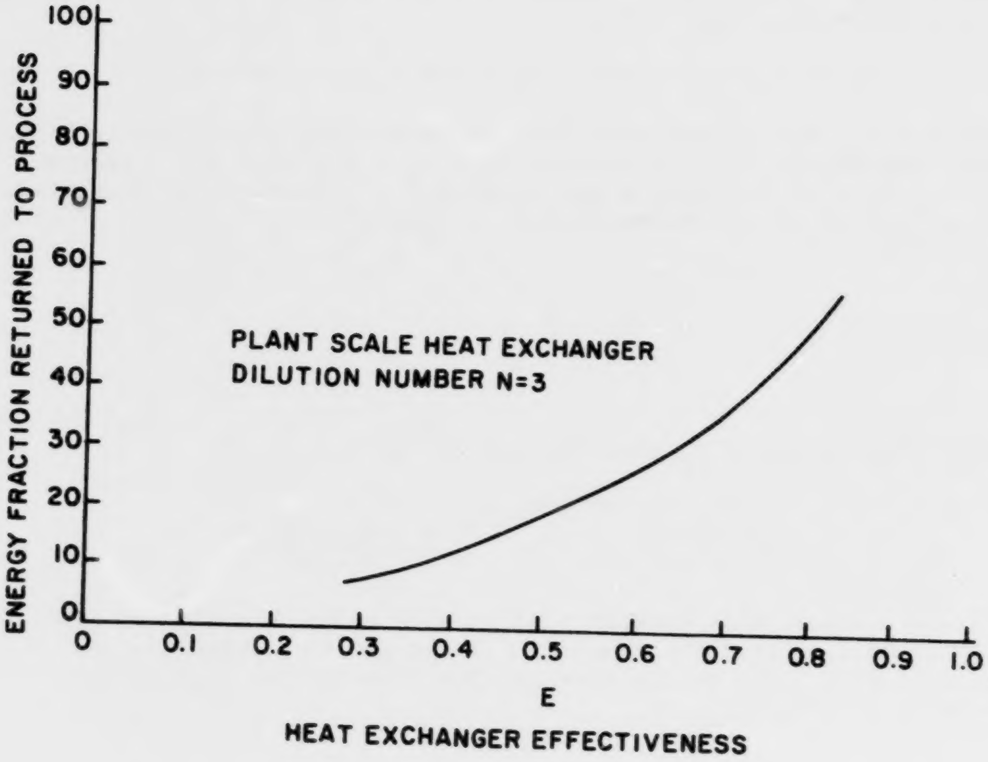

FIGURE 13 ENERGY RECOVERY BY HEAT EXCHANGERS - ATMOSPHERIC BECKS

4.1.2 Energy Recovery with Filtration Devices

4.1.2.1 Plant-scale Filtration Application - Hyperfiltration (reverse osmosis) or ultrafiltration devices offer the potential for recovery of useful industrial water from the effluent of the process. The temperature of such permeate will be at or near the temperature of the effluent. The amount of permeate produced will be less than the effluent, and thus it will be diluted with cold water to form plant inflow. It is assumed that the cold make up water is uniformly mixed with the permeate for purposes of energy computation, although non-uniform, tailored make up water addition would be potentially advantageous. The temperature rise equation (1) is valid, and with R to denote the fraction of water reused, the influent temperature obeys the equation

$$(1 - R)T_S + R(T_I + \Delta T) = T_I \tag{5}$$

Comparison with equation (2) shows that R for the filter plays the same role as E does for the heat exchanger. However, it has been assumed that the fix water must be separated from the scour and dye effluents.

4.1.2.2 Filtration Applied to Specific Processes - The foregoing has assumed that only the permeate has been recycled. Because of higher capital costs the filter systems are not apt to be justified on the basis of cost savings of energy alone, but may be justified on the basis of the sum of water, energy, chemical reclamation, and environmental benefits. On this basis, it may be that all of the effluent will not be processed, but rather only that optimum fraction which is economical. Herein, the analysis is directed toward the concept of closed cycle, processing all of the water. Also, the effluent from individual processes will require segregation for greatest recycle potential; thus, the filter systems will best be applied to specific processes. The equations for concentration (C) and temperature (T) of a well-stirred volume of mass (M) having inflow and outflow at constant rate ($\dot{m}$) are

$$M \frac{dC}{dt} = -\dot{m}(C - C_I)$$

$$Mc \frac{dT}{dt} = -\dot{m}c(T - T_I).$$

The solutions are

$$\frac{T - T_I}{T_O - T_I} = e^{-N} = \frac{C - C_I}{C_O - C_I}. \tag{6}$$

Equations (6) relate the decline in temperature (T) and concentration (C) from initial values T_o and C_o towards T_I and C_I. The value N is the ratio of $\dot{m}$ x time (= rinse mass) to process mass M.

Suppose the rinse were performed by drain and fill. If a residual volume exists in the amount of εM, each drain and fill of volume (1 - ε)M will result in a decrease in temperature and concentration of

$$\frac{T_n - T_I}{T_{n-1} - T_I} = \frac{C_n - C_I}{C_{n-1} - C_I} = \varepsilon \qquad (7)$$

The subscript n denotes the number of drain/fill cycles. Since each drop/fill increment consumes (1 - ε)M fluid, the final concentration or temperature difference ratio is related to the total rinse volume NM = n(1 - ε)M by

$$\frac{T_n - T_I}{T_o - T_I} = \frac{C_n - C_I}{C_o - C_I} = \varepsilon^{\frac{N}{1 - \varepsilon}} \qquad N = (1 - \varepsilon)n;\ n = 0, 1, 2... \qquad (7)$$

The predicted values of temperature and concentration are displayed for both the drain and fill or continuous inflow and overflow model in Figure 14. In each case it is assumed that the concentration of material on the cloth is identical with that in the beck. This assumption is valid in the limit of infinitely rapid dissolution and diffusion rates. Based on the data of Reference 5, and the time scales for the beck washing process, the assumption is reasonable for most dye substances. The drain/fill procedure uses about 30% less rinse water than the overflow procedure for a dropped volume of one-half beck and 44% less water for a dropped volume of three-quarters beck. The rinse procedure is important because when the total water use is minimized, the temperature and concentration of the mixed average effluent will be correspondingly higher and the filtration system costs will be lower. The prospect for energy conservation and economic chemical recovery is similarly greater.

The present set of assumptions indicate from Figure 14 that use of four units of rinse water in the overflow method reduces the concentration to below 2% of the original amount. Use of 2.25 units produces a slightly lower concentration in the drop/fill procedure with 0.75 beck volumes dropped and restored three times.

For the scour and dye portions of the cycle the fluid required will be one original fill, three 0.75 drop volumes after scour, and two 0.75 drop volumes after dyeing. The third 0.75 drop volume will be filled from the fixing bath permeate. Therefore the dropped amount is 6(0.75) while the refill amount needed is 1 + 5(0.75) or a ratio of 94.7%. The dropped amount may only be partially recycled and the net water recycled is some fraction of the 94.7%

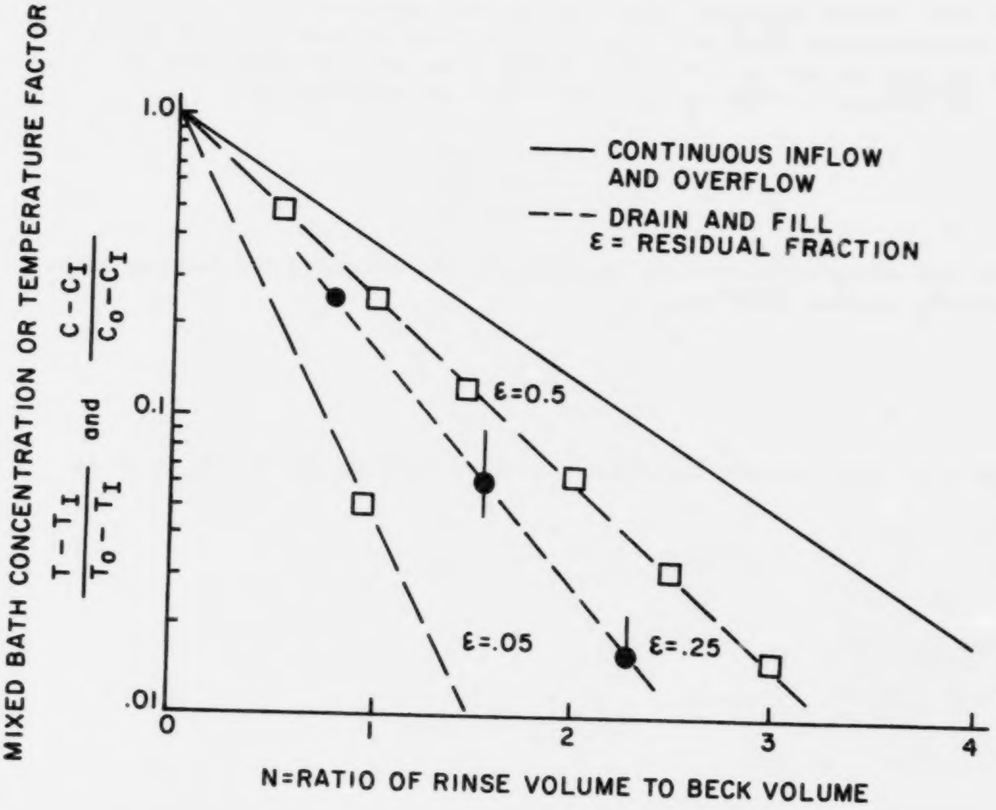

FIGURE 14 COMPARISON OF ENERGY RECOVERY WITH DROP-FILL AND OVERFLOW WASHING

which leaves the beck. It is possible to increase the 94.7% value somewhat by achieving a more complete drop at the step before fixing.

The temperature rise to T_O experienced by water at T_I used as rinse and fill water is

$$T_O - T_I = \frac{\{(74 - T_I) + (96 - T_I)\}}{1 + 5(0.75)} .$$

At a high enough recycled fraction, T_I will achieve 74 C. For recycle fractions greater than that the scour will be allowed to rise above 74 C or, equivalently, the vapor energy loss will be mitigated by recycled energy. Assuming $T_O > 74$, the rise equation is

$$T_O - T_I = \frac{(96 - T_I)}{1 + 5(0.75)} .$$

Using the above equations as appropriate and assuming the makeup water source T_S is 18 C results in

$$\frac{T_I - T_S}{T_O - T_S} = R$$

where R is the recycled fraction. The energy savings for $T_I < 74$ is

$$\% \text{ saved} = \frac{2(T_I - T_S)}{(74 - T_S) + (96 - T_S)}$$

and if $T_I > 74$

$$\% \text{ saved} = \frac{(T_I - T_S) + (74 - T_S)}{(96 - T_S) + (74 - T_S)}$$

The computations are presented in Figure 15. At about 92% recycle $T_I = 74$ C is achieved. With full recycle (94.7%) some 89% of the energy of water heating may be recovered.

A similar calculation for the fix cycle portion has been performed. More water emanates from the process than is added by a slight amount. High recovery membrane units may then produce a local excess of water. Figure 15 also shows the relation of energy recycle to water recycle for the fix portions. It is essentially the same relation as for the scour and dye cycle portions.

It is estimated that by recycle of 90 to 95% of the water between 80 and 90% of the hot water energy may be recycled to the process. The hot water represents half of the total energy requirement, so that 40 to 45% of the total energy is achievable by recycle.

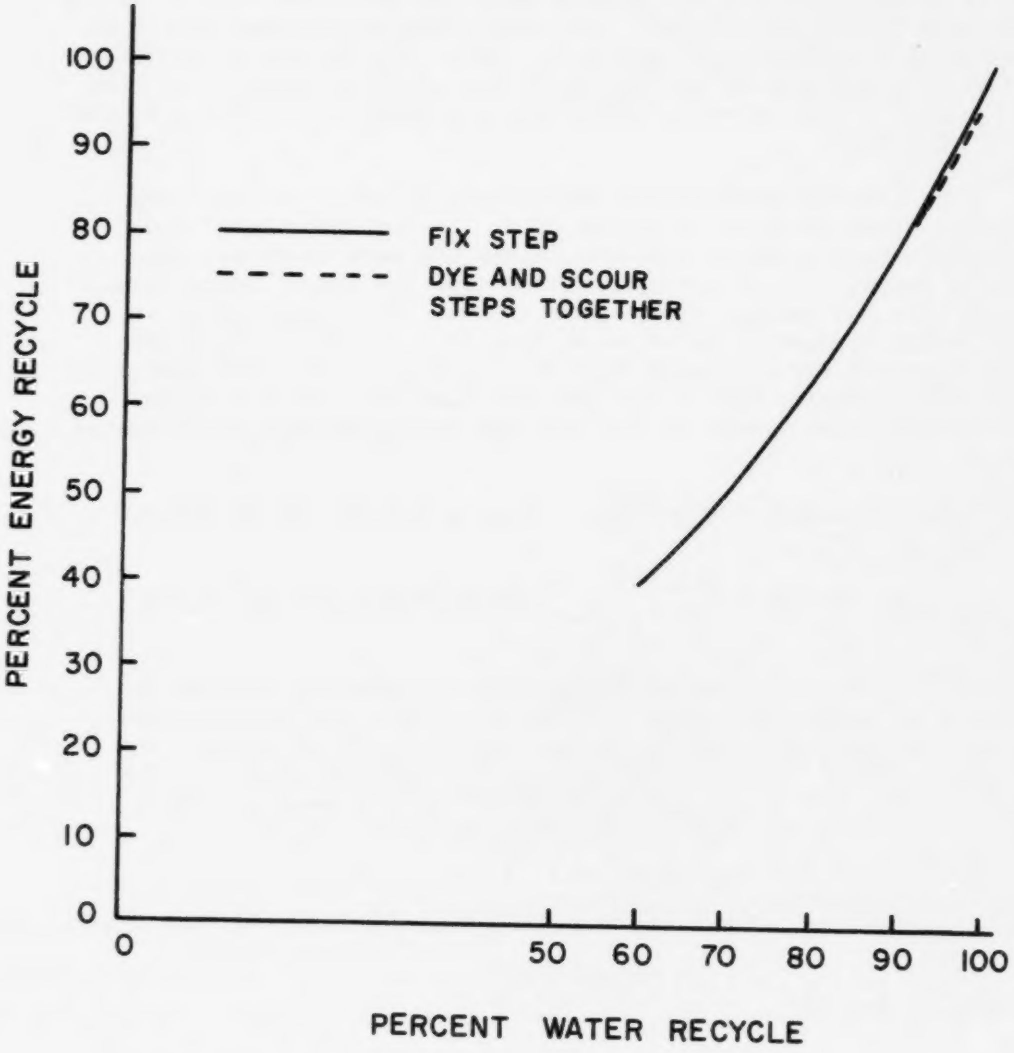

FIGURE 15 ENERGY RECOVERY RELATED TO WATER RECOVERY

4.2 Pressure Beck

Evaluation of the energy recoverable in pressure beck dyeing is subject to the same type of analysis and general restrictions as for the atmospheric becks. In the pressure beck, however, cooling from high temperature is done by a heat exchanger with process water. Any attempt to use the process water soon will overflow the process. It is interesting that the process water is not being used as makeup for beck filling at present. Such use could be arranged easily by employing a temporary storage tank. Certainly the use of membranes to recover one unit of energy is not economically competitive with the use of a tank to store heated process water to recover one-half unit of energy.

The pressure beck uses steam to heat to 110 C or 121 C and process water cools it to around 85 C. Several dye "adds" are made with excursions to dye temperature and back to 85 C. The energy needed to heat water from 18 C (average annual temperature) to 85 C is the maximum recoverable amount. The total energy to heat water is that to raise water from 18 C to 110 or 121 C plus that required for excursion from 85 C to 116 or 121 C for each dye add. Assuming that N dye adds are made and that 90% energy reuse (95% water reuse) is achieved the energy savings is estimated as

$$\%\text{ savings} = \frac{0.9\ (67)}{103 + 36N} \quad \text{high pressure (121 C) dyeing}$$

$$\%\text{ savings} = \frac{0.9\ (67)}{98 + 31N} \quad \text{low pressure (110 C) dyeing}$$

Table 15 shows the expected energy recovery possible through the recycle of spent dye baths. The table is based on the estimated water heating requirement of 80% of the total energy use for the pressure becks. In each of the cases the recycled energy is the same amount, but as the number of "adds" is increased the total energy increases so that the recycled percentage diminishes.

TABLE 15. ENERGY RECOVERY ESTIMATES FOR PRESSURE BECK DYEING

	Percent Energy Recovery	
Number of Dye Adds	High-pressure Dyeing (121 C)	Low-pressure Dyeing (110 C)
0	47%	52%
1	34%	41%
2	27%	34%
3	23%	29%

There is one possible reservation associated with the recovery of fluid for pressure beck dyeing. The material survey from the bath indicated that salts were added to the dye fluid in the amount of about 2%. Recovery of 95% of the water as implied above will raise the salt concentration to a relatively high value. At such a high value, the osmotic pressure of the concentrate will begin to cause lower fluxes or higher operating pressures. Also dye precipitation and finally salt precipitation may occur each with attendant problems.

4.3 Dye Range and Preparation Range

The energy recoverable from drain water on the range is, except for direct heat losses to the environment, exactly proportional to the water recycled. In situations where chemical concentrate recycle is practical, the recovery will be high as demanded by the chemical bath. In most cases the chemical will be required to be added at or above the concentration used at present to insure no overflow of the saturator. In situations where chemical concentrate is not recycled, the recovery level may not be as high. The dye range is expected to be a high recovery (98%) situation whereas the preparation range is only projected to recovery levels of 90% due to the very high solids loading and low probability for chemical reuse.

4.4 Summary of Energy Recovery Estimates

Table 16 shows in summary the expected savings for each process when water recycle is practical. The number of dye adds has been estimated as shown in Figures 6 and 7 to be 1 and 3, respectively, for the low- and high-pressure becks. Recovery of energy from concentrate has not been credited in Table 16, and realistic volume recovery levels have been estimated in agreement with the test results in following sections.

TABLE 16. POTENTIAL FOR ENERGY SAVINGS BY WATER REUSE - SUMMARY

	Total Energy kJ/kg cloth	Hot Water Energy kJ/kg cloth	% Volume Recovery estimated	Savings Potential kJ/kg cloth	Savings %
Atmospheric beck	4.47×10^4	2.29×10^4	95[b]	2.05×10^4	45
Pressure beck					
low-pressure	4.79×10^3	3.83×10^3	95[b]	1.96×10^3	41
high-pressure	1.15×10^4	9.11×10^3	95[b]	2.6×10^3	23
Dye range[a]	3.95×10^3	2.55×10^3	95	2.43×10^3	62
Open-width preparation range	9.3×10^3	7.08×10^3	82	5.84×10^3	62
Rope preparation range	4.34×10^3	3.29×10^3	80	2.64×10^3	61

[a] Includes only "wet" portions of the range

[b] The savings potential for batch processes is not simply the volume recovery - Hot Water Energy product

5.0 SCREENING TESTS

Samples obtained from the various effluent sources were subjected to screening tests for preliminary evaluation. The data were used to guide in the selection of promising membrane/effluent combinations for in-depth testing, to indicate problems with the particular fluids, and to allow cursory economic-based estimates.

5.1 Facility

The screening tests were conducted in a mobile (trailer) laboratory on loan to Clemson by ORNL. The trailer was located at the university during the testing activity. The laboratory was equipped with two independent systems shown schematically in Figure 16. The low-pressure system utilized a multistage centrifugal pump capable of delivering 3.4 m^3/hr (15 gpm) at 3.4 MPa (500 psig). Pressure, flow rates, and temperature were controlled manually. The internal pump parts limited the temperature of operation to 71 C (160°F).

The high-pressure loop utilized a positive displacement diaphram feed pump. The circulation velocity was maintained with a canned-rotor centrifugal pump capable of delivering 23 m^3/hr (100 gpm) at 1.03 MPa (150 psid) differential. Pressure was controlled automatically. Temperature and circulation flow rates were controlled manually. The system is constructed of 300-series stainless steel. Complete details of the facility are given in Reference 4.

5.2 Procedure

The fluid was shipped from its source to Clemson in barrels and was run as quickly as practical. The following procedure was adopted for normal operating conditions.

(1) Check flux and rejection (conductivity) of each membrane in a 100 mg/ℓ NaCl solution. Drain system.

(2) Clean prefilters and collect a one-gallon sample of raw feed from the waste to be run. Adjust pH of the waste if

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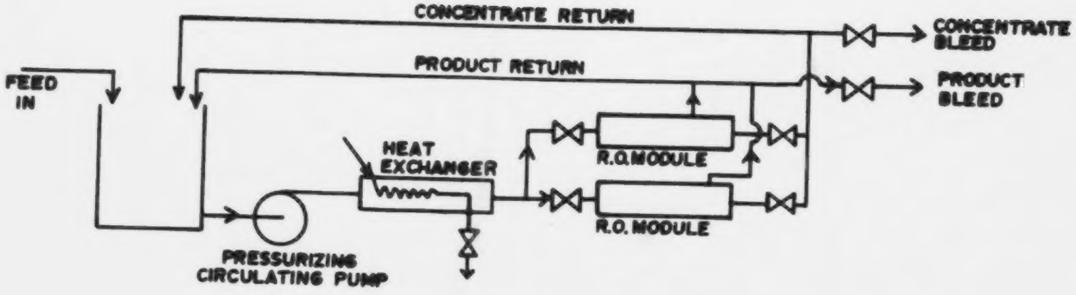
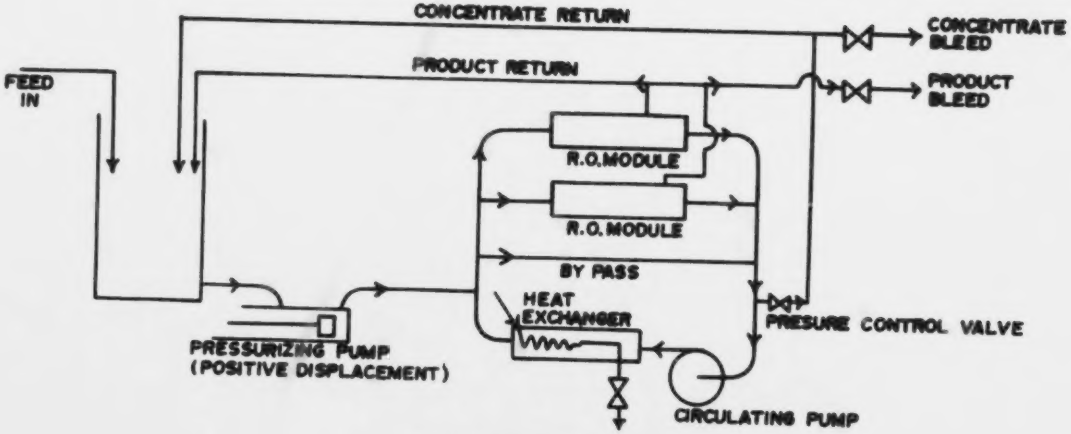
[4] Dahleimer, J. A., D. G. Thomas, K. A. Kraus, and J. R. Love, "Applications of Hyperfiltration to Treatment of Municipal Sewage Effluent," FWQA Report ORD-17030EOH01/70, 1970.


CONCENTRATE RETURN
PRODUCT RETURN
FEED IN
CONCENTRATE BLEED
PRODUCT BLEED
HEAT EXCHANGER
R.O. MODULE
R.O. MODULE
PRESSURIZING CIRCULATING PUMP

LOW PRESSURE LOOP


CONCENTRATE RETURN
PRODUCT RETURN
FEED IN
CONCENTRATE BLEED
PRODUCT BLEED
R.O. MODULE
R.O. MODULE
BY PASS
HEAT EXCHANGER
PRESURE CONTROL VALVE
PRESSURIZING PUMP (POSITIVE DISPLACEMENT)
CIRCULATING PUMP

HIGH PRESSURE LOOP

FIGURE 16 SCHEMATIC LOOPS IN MOBILE HYPERFILTRATION LABORATORY

necessary after taking samples.

(3) Pump pH-adjusted waste through prefilters. One 55-gallon barrel will be processed. Set up a 55-gallon barrel for collection of composite permeate.

(4) Start system and take initial data at 0% recovery. Data should be taken twice daily thereafter until the end of run.

(5) At the end of the run perform a four-point temperature excursion while recycling permeate to feed tank.

(6) Collect the last gallon of permeate before shutdown.

(7) Collect two gallons of composite permeate water.

(8) Collect two gallons of final concentrate.

(9) Flush system with tap water. Samples should be logged in the sample logbook and labeled appropriately. Barrels of composite permeate water should be clearly identified for future reference.

Rejections monitored include conductivity and turbidity or color.

The typical operating parameters and prefiltration methods are given in the table below.

Membrane	Pressure	Temperature	pH	Velocity	% Recovery
Zr-PAA	800	60 - 70	4.5 - 8.5	10 - 15 fps	70 - 80
Zr-sodium silicate	250	60 - 70	4.5 - 12	4 - 5 fps	75 - 90
Union Carbide	75	60 - 70	2.0 - 12	20 - 30 fps	75 - 90

Summary of samples taken:
1 gallon of raw feed
1 gallon of treated feed (if applicable)
1 gallon of final permeate
2 gallons of final concentrate
2 gallons of composite permeate

The screening test fluids were subjected to ultrafiltration or hyperfiltration according to the most favorable estimate for application. Three types of membranes were selected for test purposes.

(1) Union Carbide 3 NJR tubular ultrafiltration (UC)
(2) Zr-sodium silicate tubular ultrafiltration (Zr)
(3) Zr-PAA tubular hyperfiltration (Zr-PAA)

These membranes are listed in order of increasing rejection and generally reverse of the permeate production rate. All fluids were not subjected to all membranes. Table 17 indicates the combinations tested.

Figures 17 through 21 show the results of testing in the screening program. The data include rejection of conductivity and rejection or turbidity or color on cloudy or colored solutions as appropriate.

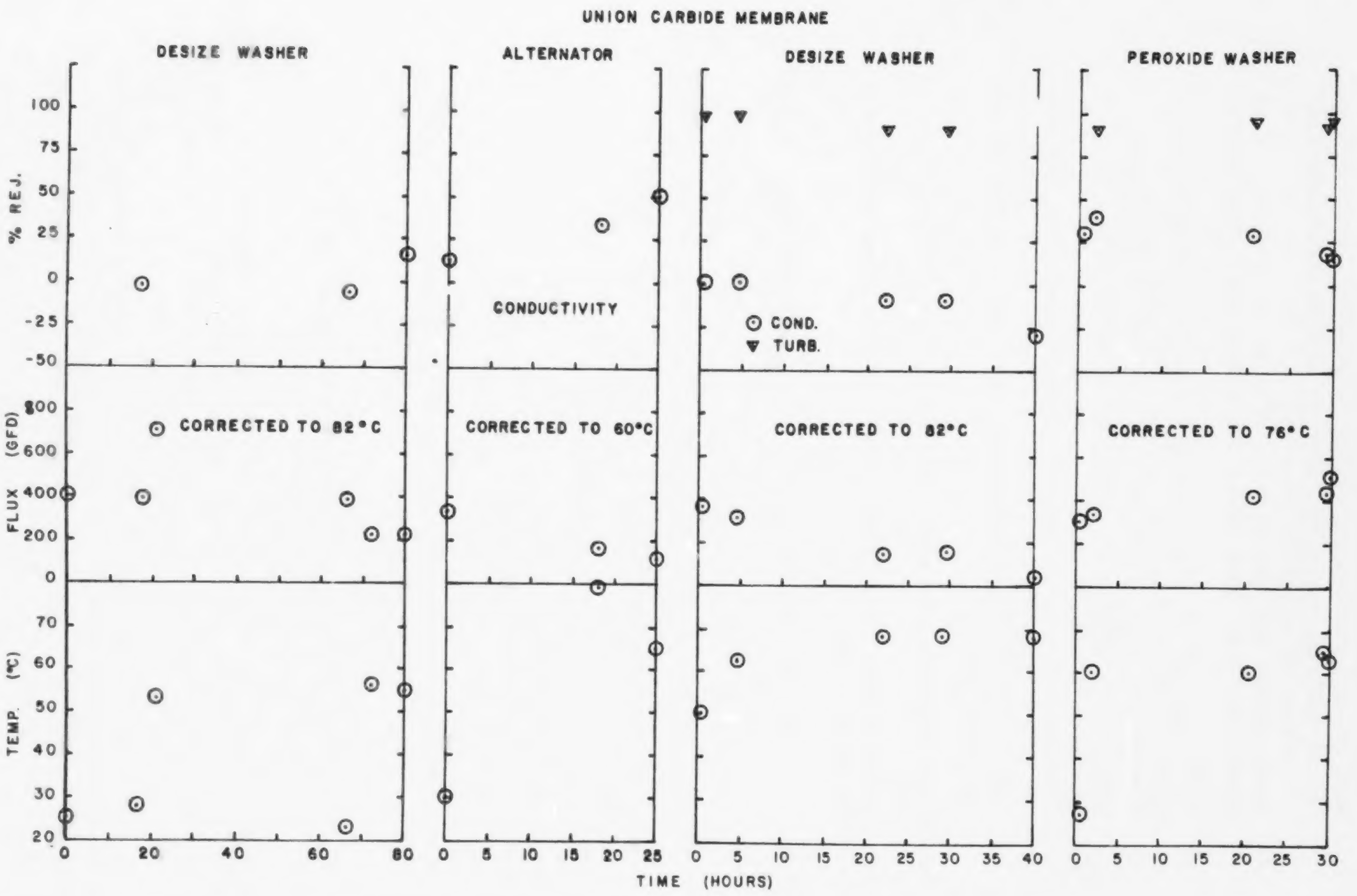


FIGURE 17 SCREENING TESTS - ULTRAFILTRATION ON OPEN WIDTH PREPARATION RANGE

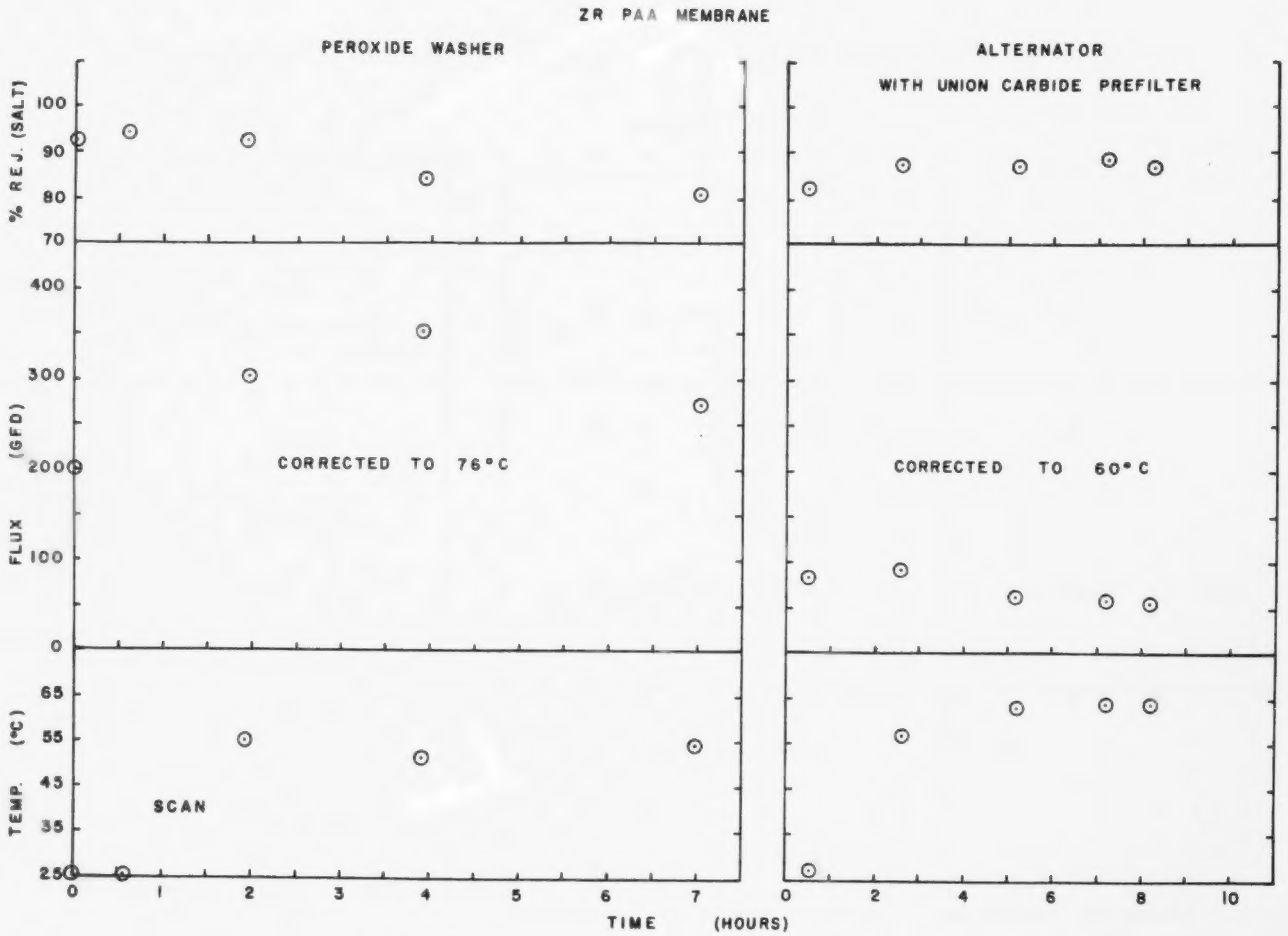


FIGURE 18 SCREENING TESTS - HYPERFILTRATION ON OPEN WIDTH PREPARATION RANGE

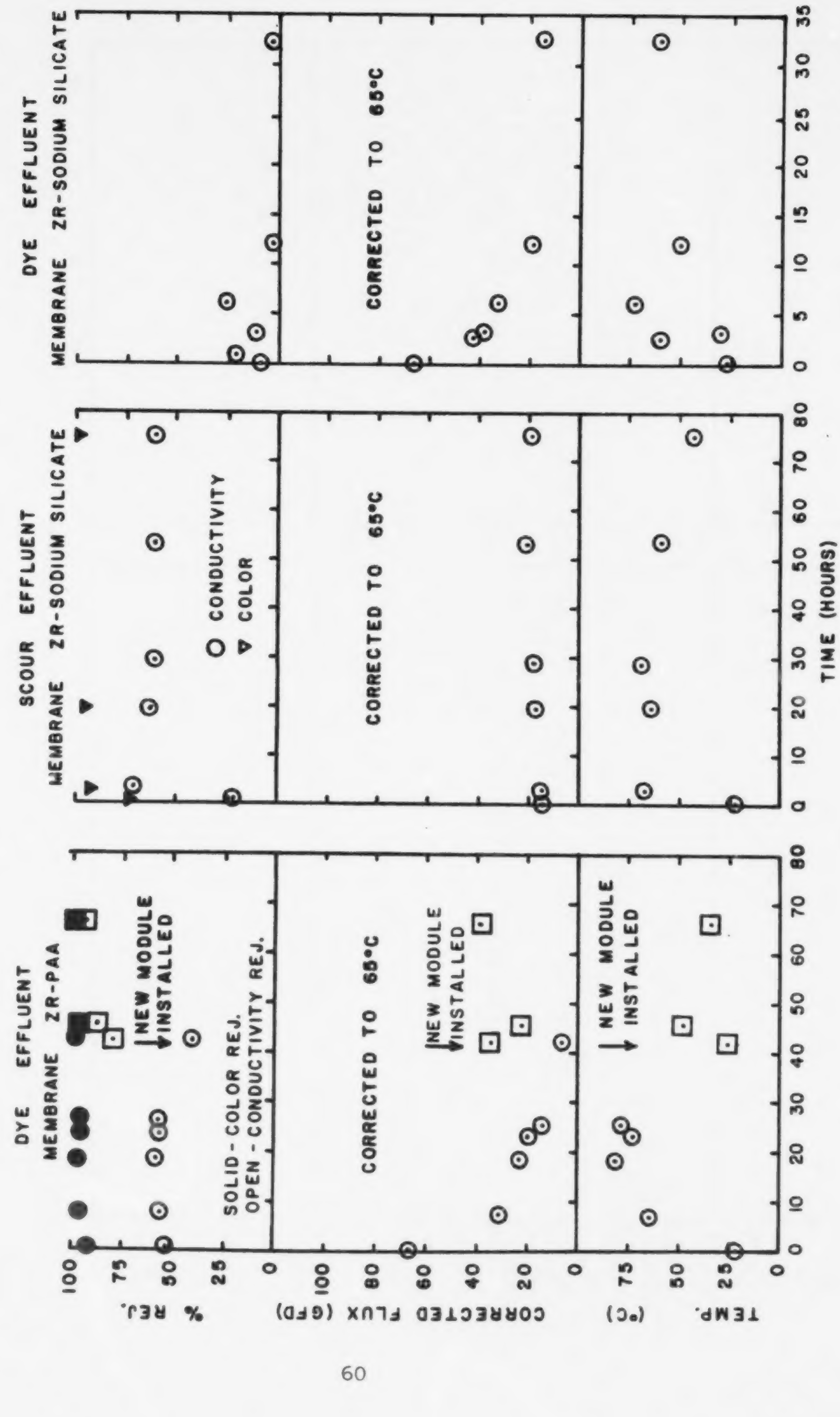


FIGURE 19 SCREENING TESTS - HYPERFILTRATION ON ATMOSPHERIC DYE BECK

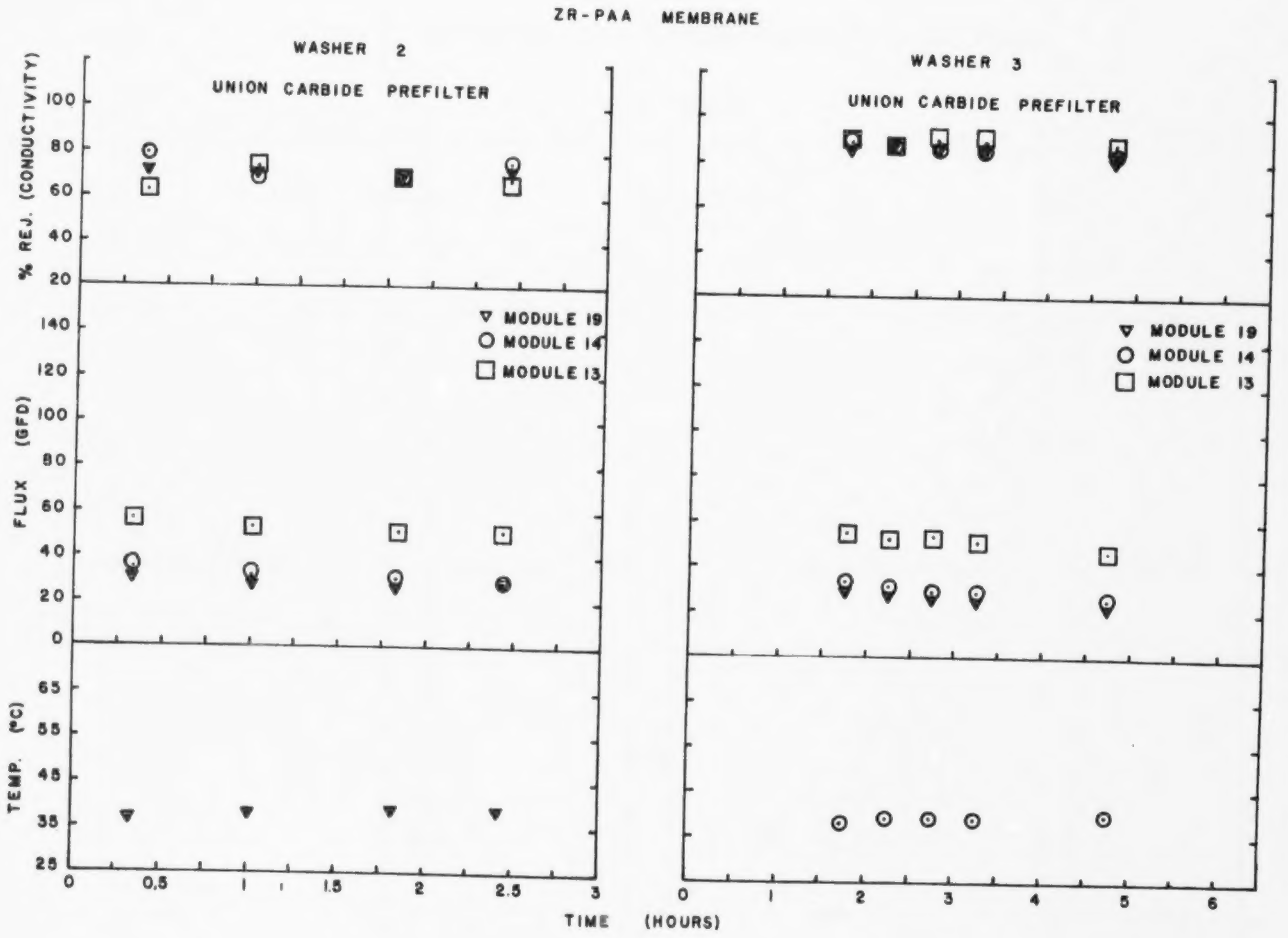


FIGURE 20 SCREENING TESTS - ROPE PREPARATION RANGE

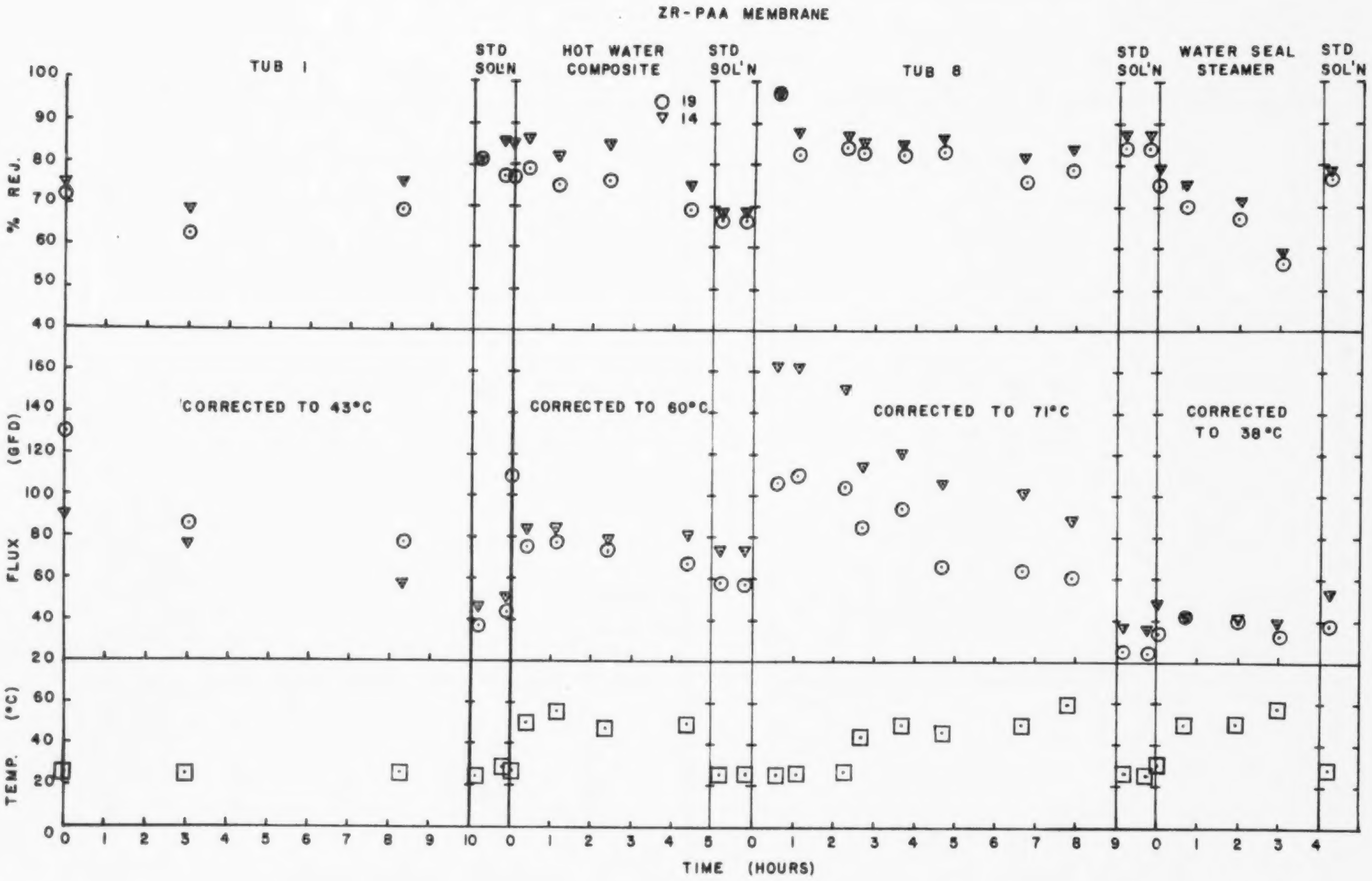


FIGURE 21 SCREENING TESTS - HYPERFILTRATION ON DYE RANGE

The data obtained from the temperature scans was used to adjust the measured permeate flow to the level expected at each process temperature. The data show the actual temperature of operation and the flux corrected for temperature to the level indicated on the figure. In each fluid category the time variations observed are shown as the fluid was processed toward the 70-90% recovery level. Therefore the feed solution is becoming more concentrated as time progresses.

TABLE 17. SUMMARY OF TESTS UNDERTAKEN

Fluid Source	Membrane	Pretreatment
Open-width Preparation Range		
Alternator washer	UC	None
Alternator washer	Zr-PAA	UC as prefilter
Desize washer	UC/Zr	None
Peroxide washer	UC	None
Peroxide washer	Zr-PAA	pH neutralized
Atmospheric Dye Beck		
Scour effluent	Zr	None
Dye effluent	Zr	None
Dye effluent	Zr-PAA	None
Rope Preparation Range		
Washer #2 (desize)	Zr-PAA	UC as prefilter; pH neutralized
Washer #3 (scour)	Zr-PAA	UC as prefilter; pH neutralized
Dye Range		
Tub #1	Zr-PAA	pH neutralized
Hot water composite	Zr-PAA	pH neutralized
Tub #8	Zr-PAA	None
Water seal on steamer	Zr-PAA	pH neutralized

The operation of the ultrafilter on the open-width preparation range fluids was reasonably uneventful as shown in Figure 17. Fluxes are reasonably high and the clarity of product water was excellent. Some conductivity rejection was registered on the alternator due to separation of the CMC size agent in the water. The negative rejection shown for the second desize washer is not understood and is perhaps spurious. The rejections recorded on the peroxide washer fluid are low but consistent. It is not known what constituent may be responsible for conductivity rejection.

Operation of the Zr-PAA membrane on the peroxide washer effluent (Figure 18) showed high fluxes and reasonably high rejections. Similarly the operation on the ultrafiltered alternator feed was uneventful and showed a normal flux level.

Operation of the hyperfilter on atmospheric dye waste effluent (Figure 19) showed high color separation and low conductivity (salt) rejection. A second membrane was installed which had improved salt rejection. Even during the short test period there was an obvious flux decline in the first membrane.

The zirconium-sodium silicate membrane showed high color rejection and high conductivity rejection for the scour fluid. The flux level was fairly low but stable. When subjected to dye fluid, the (salt) rejection was low as expected at the higher ionic strength, and the flux showed a rapid decline.

Figure 20 shows the results of testing on the rope preparation range test fluids. All monitored parameters appeared to be stable. Both the level of rejection and flux were moderate during the test.

The dye range fluid tests are summarized in Figure 21. Operations were within the normal range expected. The rejections were systematically lower in tub #1 and on the water seal, probably due to the greater ionic strength of feed. Operation on the fluid from tub #8 had an immediate restorative effect on the rejection which had declined during exposure to the hot water composite. Operation on tub #8 showed a decline in permeate flux which could be minor adjustment or the start of a long term decline. Longer testing durations are required to be more definitive. The flux levels (excluding the low temperature water seal) are of favorable magnitude.

All fluxes shown are labeled "flux corrected to xx°C" where the value xx is the temperature at which the processing is anticipated. The operation of the test was, in general, not conducted at constant temperature. At one point in the run a scan of temperature, in steps, was imposed and flux data collected. This curve was used to correct the flux data at actual test temperature to that designated for the process. The following procedure was used. Using the temperature scan data, the best value α was selected according to a plot of

$$\ln J = A - \alpha/T$$

The value of α is the slope of the line on a plot of $\ln J$ vs. T^{-1}. Using the value of α for a given fluid and membrange, the value of $J(T_o)$ which is the flux corrected to temperature T_o is determined from

$$J(T_o) = J \exp \{+ \alpha [\frac{1}{T} - \frac{1}{T_o}]\}.$$

Here J is the observed flux at temperature T. Presumably the value of $J(T_o)$ only depends upon pressure, time, etc., without dependence on temperature. Common values of 2200 to 2900 (K^{-1}) are observed. Use of such a procedure allows a plot of data to reveal trends which are not due to temperature effects. For example, assuming a value of $\alpha = 2500$ to fit the data, an observed flux of 1×10^{-5} m/s at 41 C (314K) corrected to 66 C (339K) would be

$$J\ (339K) = 1 \times 10^{-5} \exp [2500\ (\frac{1}{314} - \frac{1}{339})] = 1.8 \times 10^{-5}\ m/s.$$

The corrected flux is that flux which would be expected in a duplicate experiment run at temperature T_o.

6.0 FIELD TESTING

Because experience had indicated the need to process waste as it emanates from its particular source, a small movable test unit was constructed. The unit was designed to provide some automatic process controls while others were omitted. The operating parameters pressure, temperature, pH, and velocity could each be controlled independently. We selected to provide automatic control for pH and pressure while depending on hand-operated valves to maintain relatively fixed levels of velocity and temperature. The unit was designed to include an operation package and an instrument package. The operational package was set up to perform all basic functions without the presence of the instrument package. Also the operational package was supplied with safety cutoffs for out-of-range conditions.

A schematic of the skid-mounted test unit is shown in Figure 22. Waste feed is pumped through a float valve which maintains the level of fluid in the reservior. It is mixed in the reservoir with concentrate returning from the module and pH correction fluid (as applicable) from the reagent tank. The mixed fluid enters a small boost pump which forces flow through the particulate filter and supplies the net positive suction head of the high-pressure pump. High-pressure flow passes through the heat exchanger where its temperature is moderated by cooling water. The flow then is split between the primary module flow and a bypass flow which allows velocity control in the module. A turbine meter in the module flow circuit allows measurement of flow. The rejoined flow then normally passes through the automatic pressure control valve and is split into a small concentrate flow and the concentrate which returns to the reservoir. The module produces a permeate flow of a few tenths of dm^3/min and the through flow ranges upward from 10 dm^3/min. Therefore, the module exit concentration is about only 1% greater than the inlet concentration. The module exit flow and the bypass flow and the feed tank all have essentially the same concentration at any time. Changes in concentration are only produced slowly by control of the relative amount of concentrate and permeate released.

The dimensions of the unit are: length = 2.3 m (7 feet); width = 1.07 m (3.5 feet); and height approximately 1.52 m (5 feet) to the highest point. The dimensions have been minimized for easiest incorporation into on-site locations. Besides the waste, the unit requires approximately 8 liters per minute (2 gpm) of coolant flow and 230 volt, 3 phase, four wire electrical power of 50 amperes.

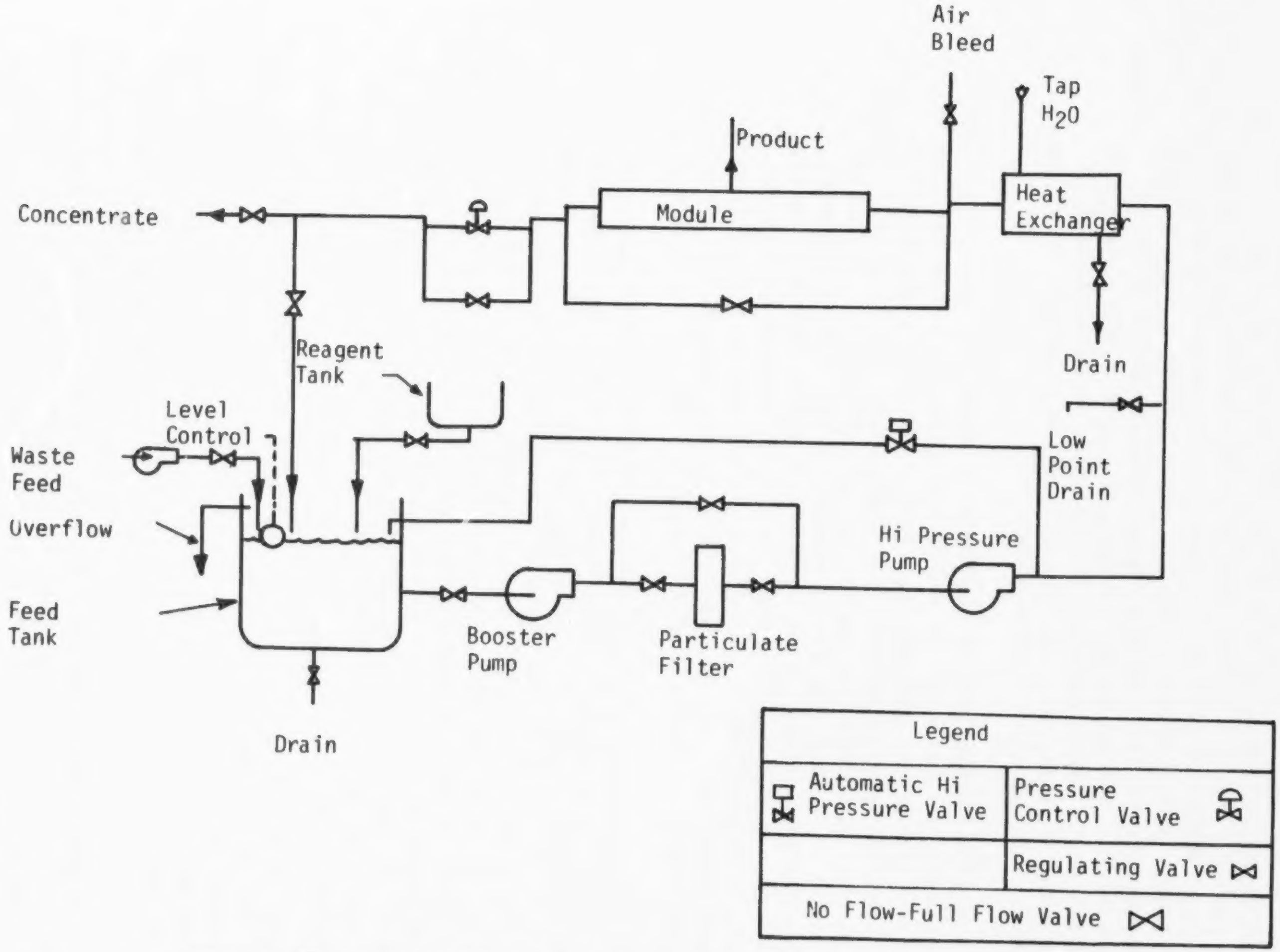

Air Bleed
Tap H_2O
Product
Concentrate
Module
Heat Exchanger
Drain
Reagent Tank
Level Control
Waste Feed
Overflow
Feed Tank
Low Point Drain
Hi Pressure Pump
Booster Pump
Particulate Filter
Drain
Legend
Automatic Hi Pressure Valve
Pressure Control Valve
Regulating Valve
No Flow-Full Flow Valve

FIGURE 22 FLOW SCHEMATIC OF SKID MOUNTED UNIT

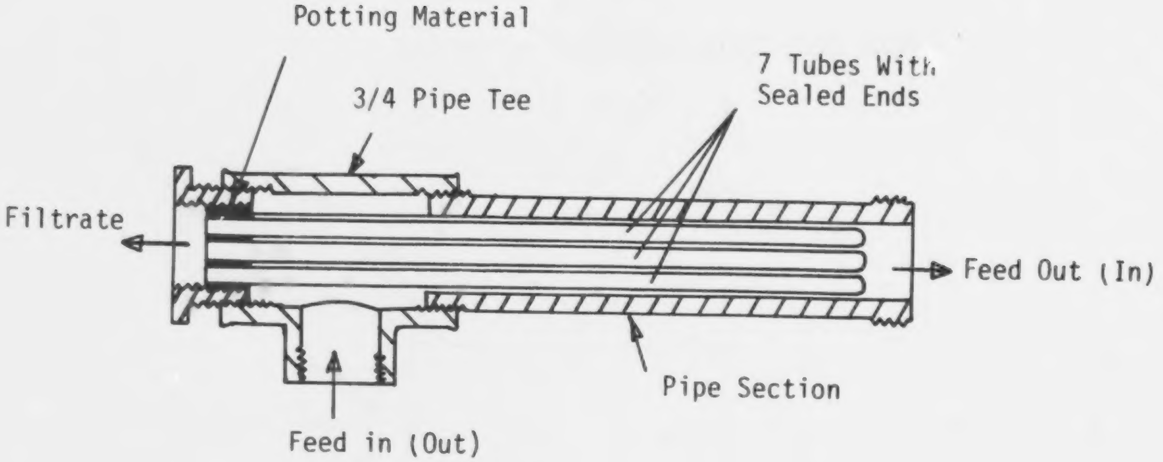
The modules consisted of a bank of ceramic tube modules and a module incorporating stainless steel tubes. The modules have dynamically formed ZrO-PAA membranes.

The basic ceramic tube module is shown in Figure 23. Each element of the module consists of seven tubes individually potted into a plug which will thread into a pipe tee. The free ends of the tubes are sealed, and the potted ends permit flow into a filtrate chamber. This flow in turn can be readily collected with adjacent filtrate flows. Flow passes along the tubes within a pipe fitted to the tee outside of the ceramic tubes. The feed can flow in either direction. One candidate method of joining the elements is shown in Figure 23. This method is reasonably economical and relatively easy to assemble. An assembly of 30 elements is equivalent to about 0.87 m^2 of membrane area.

The stainless steel module assembly is shown in Figure 24. In this arrangement the pressure is applied within the tubes and the permeate is collected by the shell. Feed flow enters one tube, is routed to another tube by appropriate cutouts in the flow routing sheet, and finally exists the opposite end. Each tube is sealed by an "O" ring on a tube end piece welded to the filter support tube. Flat gaskets prevent flow between adjacent channels, while flow out of the system is prevented by an "O" seal on the faces of the routing sheet. The three-piece bundle end is bolted together (not indicated by the figure), and the ends are joined by rods which are in slight tension. The membrane area is 0.95 m^2 for the module.

An ultrafiltration skid was constructed having the same general description as the hyperfiltration skid. The pump which was found unsatisfactory for hyperfiltration service was used with a one horsepower motor. A variable area flowmeter was located downstream of the test section which was bypassed by an appropriately valved line allowing flow control up to 42 dm^3/min (11 gpm) through the test section. Pressure readouts were located upstream and downstream of the test section. The feed was filtered through a 25 micron cartridge filter and added to a stainless steel tank normally maintained at a 76 dm^3 (20 gallon) level. All metal parts were 300 series stainless steel with connections made of industrial rubber hose.

No heat exchanger was provided since at the lower pressure level of operation the energy buildup was slight. However, this lack of energy buildup proved to be some problem since in low throughput cases the performance data were obtained at low temperature making interpretation difficult. The throughput could be increased by having permeate flow all pass to the drain or increasing the flow of concentrate to the drain. With higher throughput rates the feed barrel would be exhausted soon after a feed flow interruption. The source fluid was interrupted frequently on the dye range in association with shade changes. The automatic low level cutoff would shut down the unit and, when unattended, the operation would be discontinued.


Potting Material
3/4 Pipe Tee
7 Tubes With
Sealed Ends
Filtrate
Feed Out (In)
Pipe Section
Feed in (Out)

CERAMIC TUBE MODULE ELEMENT

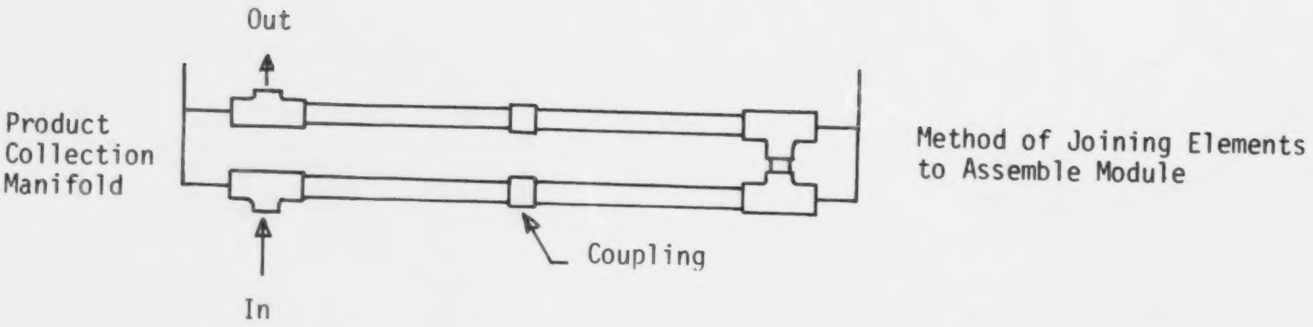

Out
Product
Collection
Manifold
Method of Joining Elements
to Assemble Module
Coupling
In

FIGURE 23 CERAMIC TUBE MODULE ARRANGEMENT

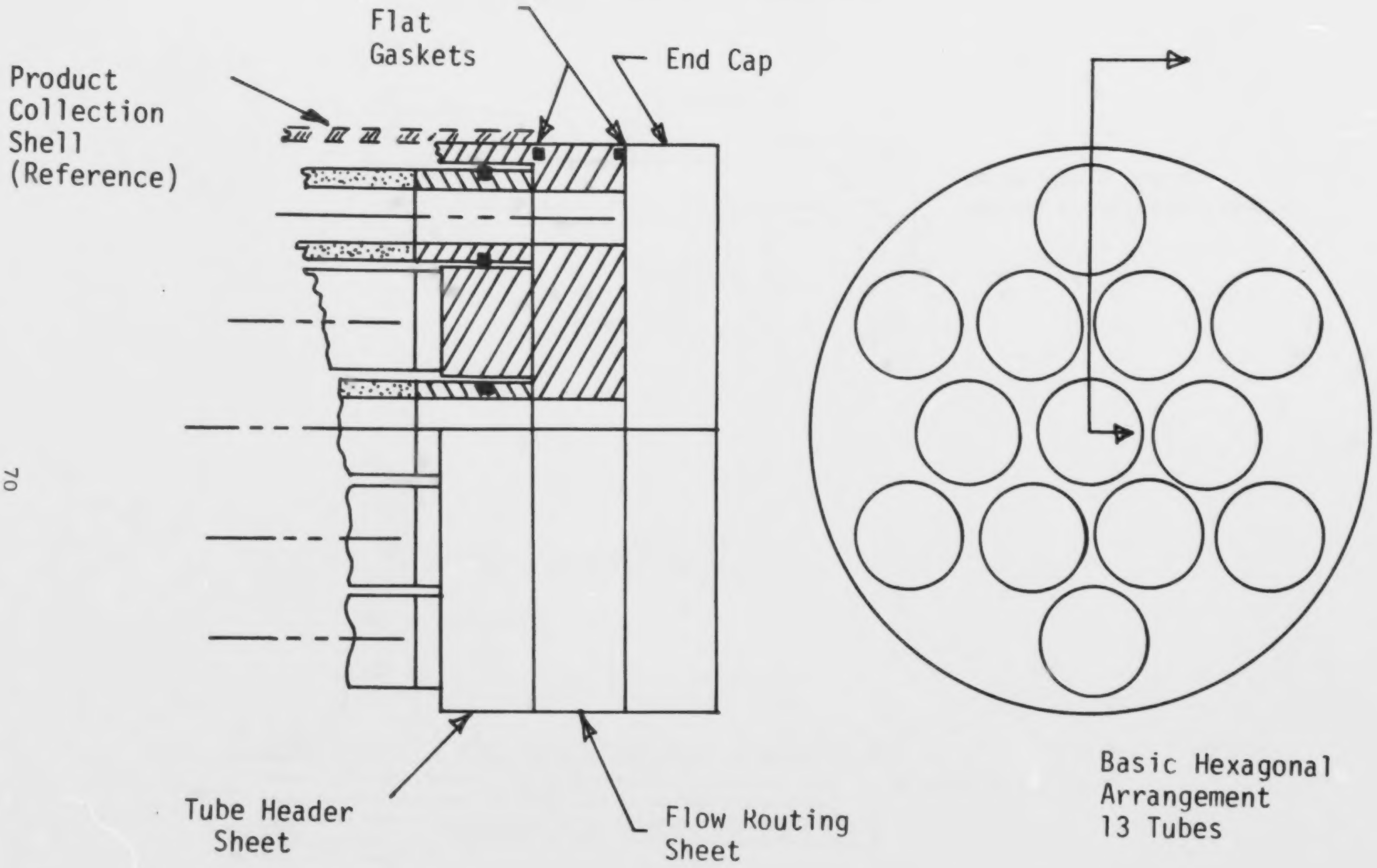

Product
Collection
Shell
(Reference)
Flat
Gaskets
End Cap
Tube Header
Sheet
Flow Routing
Sheet
Basic Hexagonal
Arrangement
13 Tubes

FIGURE 24 STAINLESS STEEL TUBE MODULE

As shown in Figure 25, the three modules were located in series, each having similar flow requirements, in order to use one flow meter. The UC 3 NJR and ZrO permeate flows are less than 1% of the feed flow so that each module was exposed to the same fluid. The permeate from the Union Carbide and ZrO dynamic membrane were normally diverted to drain, while the larger Abcor module permeate flow was returned to the feed. The latter permeate return arrangement was decided after experiencing considerable difficulty in maintaining feed sufficient to keep up with the permeate flow. During attended runs the permeate flow was diverted to drain as required to establish the desired operating conditions.

6.1 Operation of Atmospheric Beck Dye Fluid

The skid unit was located adjacent to a dye beck together with a feed reservoir. The feed reservoir was comprised of four interconnected vessels each formed by welding a pair of 55-gallon drums end-to-end. The drums were painted with epoxy paint to alleviate corrosion and the insertion of corrosion products into the feed stream. The normal procedure for filling the feed reservoir was to pump beck fluid from a location near the drain as the beck was undergoing rinse/overflow. On some occasions the operator pumped undiluted dye liquor and in others, only a "topping off" of the feed reservoir was required. In both of these situations a more concentrated feed was delivered to the membrane unit. New fluid was added at essentially each dyeing over the test period.

The tubular stainless steel module was installed on a skid and tested for operational acceptance. Table 18 shows a skeleton of data obtained. After two weeks of operation (233 hours) the flux had degenerated to below 20% of its original value. The module was removed and replaced with a ceramic tube bundle with the resolve to carefully monitor for the presence of metal ions which could be responsible for flux decline.

Starting from January 26, 1977, twelve 7-tube ceramic bundles were operated for 502.4 hours which was 46.5% of the total time between January 26 and March 11, 1977. Figure 26 summarizes the test conditions for the period. Figure 27 shows flux versus time where the flux has been corrected to 66 C using a procedure outlined in the screening test section.

The unit was operated to provide approximately half concentrate and half product for a period of about 100 hours. The temperatures and thereby the permeate flux varied considerably, while the conductivity rejection remained fairly constant at about 80%. After the 100-hour point, the concentrate flow was reduced allowing the membranes to be exposed to more concentrated material as evidenced by the higher total solids and concentrate conductivity levels in Figure 26. The curve of Figure 27 as expected

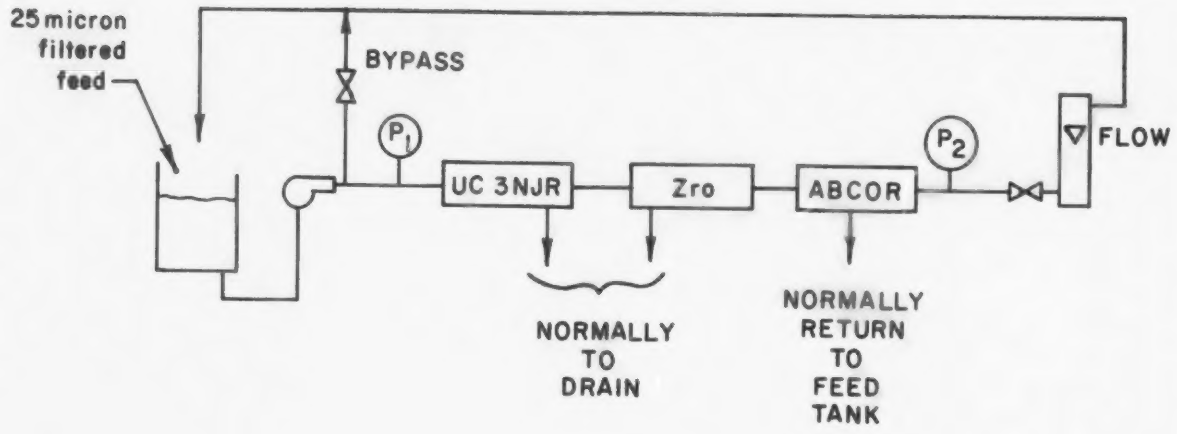

25 micron filtered feed
BYPASS
P_1
UC 3NJR
Zro
ABCOR
P_2
FLOW
NORMALLY TO DRAIN
NORMALLY RETURN TO FEED TANK

FIGURE 25 ULTRAFILTRATION SKID SCHEMATIC FLOW DIAGRAM

TABLE 18. MEMBRANE OPERATION ON DYE WASTE FROM ATMOSPHERIC BECK

Date	Pressure MN/m^2	Temperature (°C)	Flux m^3/m^2-s	Conductivity Rejection
11/29/76	Tubular stainless steel module installed.		0.95 m^2	
	$NaNO_3$ solution prior to exposure to waste.			
	5.5 (800 psig)	50	2.03 x 10^{-5} (43 GFD)	-
12/01/76	Dye waste solution.			
	5.9	75	1.23 x 10^{-5} (26 GFD)	67
12/16/76	-	<38	0.24 x 10^{-5} (5 GFD)	90
01/12/77	Ceramic 0.307 m^2 module installed.			
	$NaNO_3$ solution			
	5.5	43	2.03 x 10^{-5} (43 GFD)	87
	Dye waste solution initially.			
	5.5	52	2.6 x 10^{-5} (55 GFD)	58[a]

[a] Feed conductivity 16,000 μmho/cm.

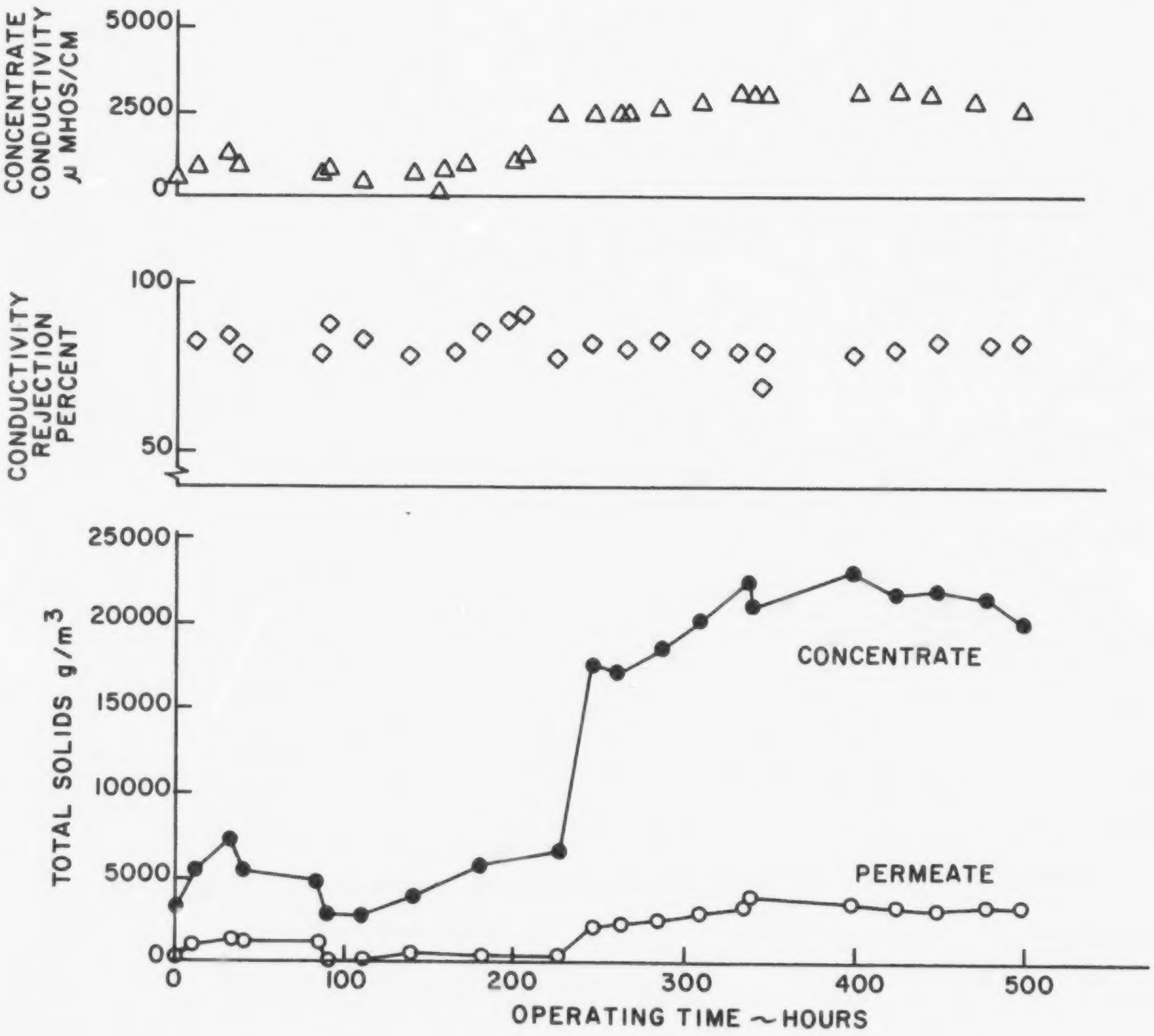


FIGURE 26 OPERATING CONDITIONS HISTORY - ATMOSPHERIC DYE BECK

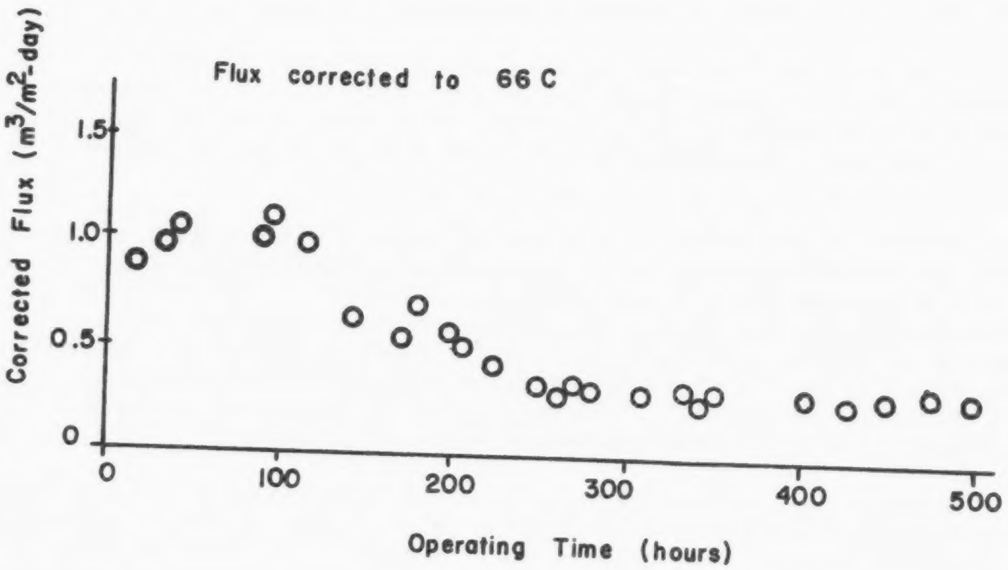


FIGURE 27 PERMEATE FLOW RESULTS - ATMOSPHERIC DYE BECK

shows little scatter due to temperature variation but does indicate the severe flux decline. The membrane appeared to stabilize in flux until 100 hours, whereafter the flux declined steadily to a level of about 2.8 m^3/m^2-s (6 GFD).

Seventy-two samples were taken during the period January 26 to March 11, 1977. These consisted of twenty-four each of concentrate, product, and feed. Analyses of these samples is shown in Table 19. The data in the table correspond to the period of testing shown in Figure 26. The samples 2022, 2023, and 2024 were extracted at about 109 hours, i.e., near the onset of the flux decline period. The only apparently significant data relative to the flux decline is that the turbidity of both feed and concentrate had jumped to "opaque" from previously being in the instrument's range. Neither total solids, calcium, or magnesium registered a significant increase near the point.

A separate decline test was performed on February 15 through February 18, 1977, using a previously unexposed membrane designated bundle L. The result is shown in Figure 28. Flux is corrected to 66 C using data from the temperature scan test performed on February 7, 1977.

Because of the correlation shown in Figure 29 between the low flux levels and the elevation in chromium and copper in the test fluid, mechanisms for the flux decline were sought. Laboratory testing confirms that copper will produce flux declines but not similar in concentration effects to those shown in Figure 29. During the period of testing the cause of flux decline was not isolated and remains to be studied. A later section of this report shows a contrasting relative effect of metals on flux to Figure 29.

A number of test dyeings were conducted using concentrated dye fluid from the hyperfiltration unit. The concentrated material was a mixture of a number of runs and was used in test dyeings matching several shades. Measurements of the dye formula required to bring the dyeing to shade were compared with standard formulations. In some cases less dye was required; in other cases, more. Little or no economic advantage is apparent; however, reuse of the concentrated dye has a decided environmental advantage.

In conducting tests for reuse the following procedure was followed. The dyes were added to a beaker containing 1% Duodye and the solution mixed well. The fabric was then introduced into the beaker and the solution was heated to 93 C for one hour. The fabric was then removed from the bath, rinsed, and dryed.

Samples of concentrate dyebath wastewater obtained from the skid hyperfiltration unit were evaluated in the plant laboratory for dye content and value for producing commercial shades. Table 20 shows data for the amount of dye required to adjust the concentrate to give a commercial shade. However, the average amount added was less than normal. Most important though was the fact that the dye concentrate was determined to be reusable in dyeing a variety of test shades.

TABLE 19. ANALYSIS OF SAMPLES FROM HYPERFILTRATION OF DYE BECK FLUID

Sample #	Date Taken	Type	Conductivity (μmho/cm)	% Rejection (Conductivity)	Turbidity (FTU)	pH
2004	1/26/77	F	1940	-	1.20	6.48
2005	1/26/77	P	520	89.6	0.64	6.61
2006	1/26/77	C	5000	-	31.00	6.42
2007	1/27/77	F	-	-	-	-
2008	1/27/77	P	1500	-	0.51	6.80
2009	1/27/77	C	8600	81.9	4.10	6.58
2010	1/28/77	P	2330	-	0.37	6.78
2011	1/28/77	C	12000	80.5	2.20	7.05
2012	1/28/77	F	3500	-	2.70	6.95
2013	1/31/77	F	-	-	-	-
2014	1/31/77	P	1820	76.0	0.42	6.92
2015	1/31/77	C	7600	-	2.10	7.30
2016	2/02/77	F	2820	-	5.20	6.90
2017	2/02/77	P	1780	72.4	0.36	6.95
2018	2/02/77	C	6450	-	1.70	7.39
2019	2/03/77	F	2150	-	0.56	7.06
2020	2/03/77	P	590	-	0.27	6.88
2021	2/03/77	C	-	-	-	-
2022	2/04/77	F	2050	-	opaque	6.65
2023	2/04/77	P	435	88.5	0.24	6.93
2024	2/04/77	C	3800	-	opaque	6.59
2025	2/07/77	F	1380	-	opaque	6.73
2026	2/07/77	P	1120	81.2	0.27	6.85
2027	2/07/77	C	5950	-	opaque	6.70
2028	2/08/77	F	1400	-	opaque	7.00
2029	2/08/77	P	1520	74.2	0.21	7.38
2030	2/08/77	C	5900	-	opaque	7.22
2031	2/09/77	F	-	-	-	-
2032	2/09/77	P	-	-	-	-
2033	2/09/77	C	-	-	-	-
2034	2/15/77	F	9100	-	opaque	7.51
2035	2/15/77	P	830	89.0	1.30	7.11
2036	2/15/77	C	7600	-	opaque	7.51
2037	2/16/77	F	9100	-	opaque	7.60

TABLE 19. (continued)

Sample #	Date Taken	Type	Conductivity (μmho/cm)	% Rejection (Conductivity)	Turbidity (FTU)	pH
2038	2/16/77	P	1200	87.8	0.88	7.39
2039	2/16/77	C	9800	-	opaque	7.78
2040	2/18/77	F	9500	-	opaque	7.83
2041	2/18/77	P	3600	85.3	0.47	7.62
2042	2/18/77	C	24500	-	opaque	7.90
2043	2/28/77	F	8400	-	-	7.61
2044	2/28/77	P	3800	84.2	0.36	7.61
2045	2/28/77	C	24000	-	opaque	8.05
2046	3/01/77	F	8190	-	opaque	7.75
2047	3/01/77	P	4150	83.4	0.53	7.80
2048	3/01/77	C	25000	-	opaque	8.08
2049	3/02/77	F	8400	82.4	opaque	7.22
2050	3/02/77	P	4800	-	0.41	-
2051	3/02/77	C	27200	-	opaque	-
2052	3/03/77	F	8300	82.0	opaque	7.30
2053	3/03/77	P	5400	-	0.35	-
2054	3/03/77	C	30000	-	opaque	-
2055	3/04/77	F	8100	78.2	opaque	7.38
2056	3/04/77	P	6100	-	opaque	-
2057	3/04/77	C	28000	-	opaque	-
2058	3/07/77	F	7050	-	opaque	7.46
2059	3/07/77	P	5550	80.5	0.28	-
2060	3/07/77	C	28900	-	opaque	-
2061	3/08/77	F	4750	-	opaque	7.31
2062	3/08/77	P	5450	79.4	0.21	-
2063	3/08/77	C	26500	-	opaque	-
2064	3/09/77	F	3600	-	opaque	7.04
2065	3/09/77	P	4700	83.2	0.19	-
2066	3/09/77	C	28000	-	opaque	-
2067	3/10/77	F	3350	-	opaque	6.94
2068	3/10/77	P	4800	82.2	0.36	-
2069	3/10/77	C	27000	-	opaque	-
2070	3/11/77	F	3120	-	opaque	6.91
2071	3/11/77	P	5000	80.0	0.58	-
2072	3/11/77	C	25000	-	opaque	-

TABLE 19. (continued)

Sample #	Color 410 µm	Color 500 µm	Color 600 µm	Total Solids (mg/ℓ)	Copper (mg/ℓ)	Iron (mg/ℓ)	Hardness Ca & Mg (mg/ℓ)	Calcium (mg/ℓ)	Alkalinity (mg/ℓ $CaCO_3$)
2004	87.9	87.3	98.0	1055	-	-	21.0	5.4	19.3
2005	92.8	96.8	95.7	308	-	-	1.6	nd	8.7
2006	81.5	88.3	93.8	3203	-	-	29.9	0.6	-
2007	82.8	89.1	95.2	5300	-	-	42.3	14.0	56.2
2008	94.9	96.2	98.9	809	-	-	3.3	nd	15.8
2009	84.1	92.1	95.1	5277	-	-	42.3	14.6	59.4
2010	92.5	97.5	99.2	1246	-	-	7.9	2.1	18.8
2011	75.2	90.5	95.8	7044	-	-	70.7	34.4	58.8
2012	83.1	95.2	98.5	1983	-	-	17.9	8.0	23.9
2013	86.9	92.9	96.5	5366	-	-	58.1	31.0	48.6
2014	93.3	95.8	96.2	939	-	-	2.9	2.1	17.2
2015	87.0	93.5	97.3	5303	-	-	57.8	30.8	42.4
2016	89.2	93.2	97.0	1701	-	-	16.7	8.4	14.9
2017	96.2	97.2	99.3	955	-	-	4.0	2.6	15.5
2018	87.9	93.4	99.0	4490	-	-	60.6	30.5	32.1
2019	93.8	91.9	95.5	992	-	-	16.5	-	21.3
2020	94.9	92.9	98.4	139	-	-	2.5	-	8.7
2021	86.5	91.8	96.9	2839	-	-	40.0	-	20.2
2022	91.9	91.9	93.9	1331	<0.20	1.20	18.6	10.4	18.5
2023	98.2	99.8	100.0	243	<0.20	0.00	1.0	0.4	18.5
2024	87.1	88.5	94.0	2696	0.00	0.24	79.0	48.5	34.6
2025	93.6	95.0	97.5	673	<0.20	0.20	11.9	8.0	17.9
2026	97.0	99.0	100.0	535	<0.20	0.04	1.6	2.6	7.7
2027	82.9	83.6	89.0	3697	<0.20	0.28	63.7	51.1	50.3
2028	93.1	95.2	97.3	684	<0.20	0.16	11.9	12.6	15.6
2029	99.0	100.0	100.0	744	<0.20	0.08	2.1	1.2	19.6
2030	74.1	76.0	83.4	3760	0.00	0.51	68.1	53.1	48.7
2031	-	-	-	-	-	-	-	-	-
2032	-	-	-	-	-	-	-	-	-
2033	-	-	-	-	-	-	-	-	-
2034	4.0	0.5	43.5	6450	0.42	0.04	20.9	-	115.5
2035	95.0	96.0	92.1	462	0.20	0.00	4.5	1.2	16.9
2036	35.0	50.0	68.5	5168	3.30	0.23	74.3	-	65.5
2037	4.7	1.5	42.3	6741	0.26	0.05	21.1	-	118.9
2038	96.5	98.9	99.8	449	0.18	0.01	4.6	1.5	19.8

TABLE 19. (continued)

Sample #		Color		Total Solids (mg/ℓ)	Copper (mg/ℓ)	Iron (mg/ℓ)	Hardness Ca & Mg (mg/ℓ)	Calcium (mg/ℓ)	Alkalinity (mg/ℓ $CaCO_3$)
	410 µm	500 µm	600 µm						
2039	11.5	13.9	55.0	6824	2.61	0.27	106.8	-	88.5
2040	4.1	0.5	39.1	6454	1.05	0.09	14.0	-	112.6
2041	98.5	99.1	99.5	2042	0.20	0.01	2.3	1.4	36.6
2042	00.0	00.0	12.0	17524	3.60	0.40	110.0	-	241.6
2043	7.0	2.1	41.0	5675	1.50	0.08	27.7	-	105.2
2044	97.1	97.5	100.0	2335	0.21	0.01	3.3	0.8	48.5
2045	00.0	00.0	7.0	17189	2.64	0.50	110.0	-	242.6
2046	7.5	2.5	41.0	5670	1.30	0.47	114.5	-	104.6
2047	96.3	97.8	99.3	2385	0.21	<0.04	5.0	1.1	42.7
2048	00.0	00.0	6.3	18695	4.32	0.08	28.8	-	271.9
2049	11.1	5.2	47.7	5710	-		23.7	-	107.2
2050	0.5	93.0	96.1	2815	-		3.7	1.0	47.4
2051	00.0	00.0	5.0	20546	-		122.5	-	294.0
2052	0.3	00.0	29.9	5690	-		23.6	-	105.2
2053	90.4	96.1	99.2	3272	-		5.1	1.7	57.3
2054	00.0	00.0	1.7	22429	-		134.9	-	322.8
2055	0.3	00.0	28.9	5680	-		23.1	-	110.3
2056	80.3	82.2	94.8	3867	-		10.9	2.4	65.7
2057	00.0	00.0	2.6	20910	-		127.7	-	310.0
2058	5.9	1.8	38.7	4813	-		20.8	-	94.5
2059	96.2	96.8	97.9	3521	-		3.5	2.1	71.0
2060	00.0	00.0	1.9	23116	-		148.5	-	357.5
2061	17.9	9.8	58.1	3180	-		14.1	-	66.5
2062	96.9	97.3	99.5	3359	-		3.0	1.6	59.7
2063	00.0	00.0	2.9	21398	-		132.5	30.9	327.5
2064	32.4	21.9	70.7	2182	-		3.4	9.2	47.6
2065	97.1	98.8	99.7	2860	-		9.3	2.8	51.1
2066	00.0	00.0	2.3	21711	-		140.2	53.9	334.6
2067	35.4	24.7	72.3	2011	-		8.5	6.6	43.6
2068	95.5	97.8	97.8	2899	-		2.8	1.5	51.9
2069	00.0	00.0	2.2	21606	-		143.8	61.3	325.2
2070	36.3	27.9	74.1	1794	-		8.0	3.8	40.3
2071	97.2	98.3	99.3	2909	-		5.6	2.8	52.5
2072	00.0	00.0	1.9	19948	-		139.0	61.7	298.9

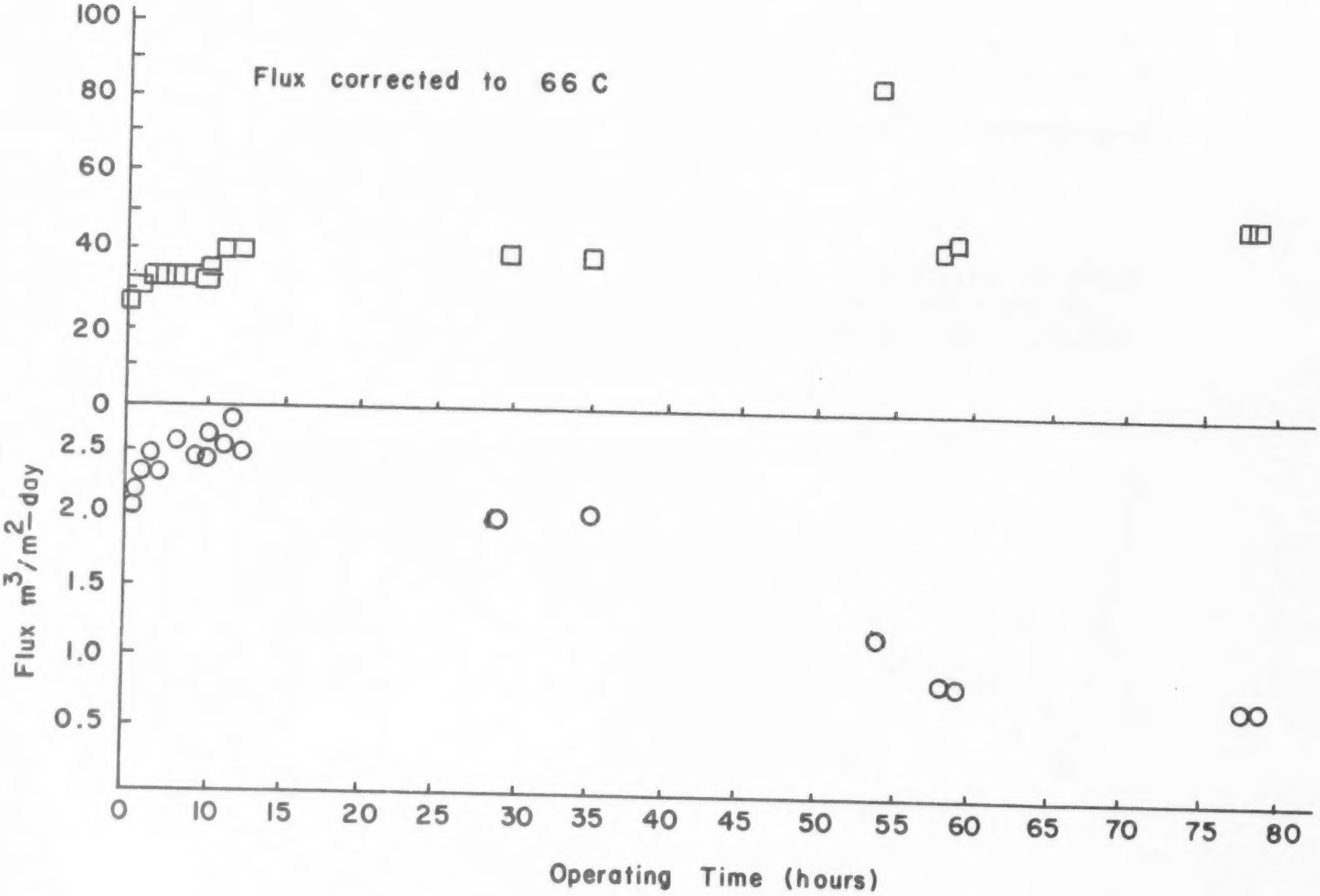


FIGURE 28 RESULTS OF FLUX DECLINE STUDY WITH ATMOSPHERIC DYE BECK FLUID

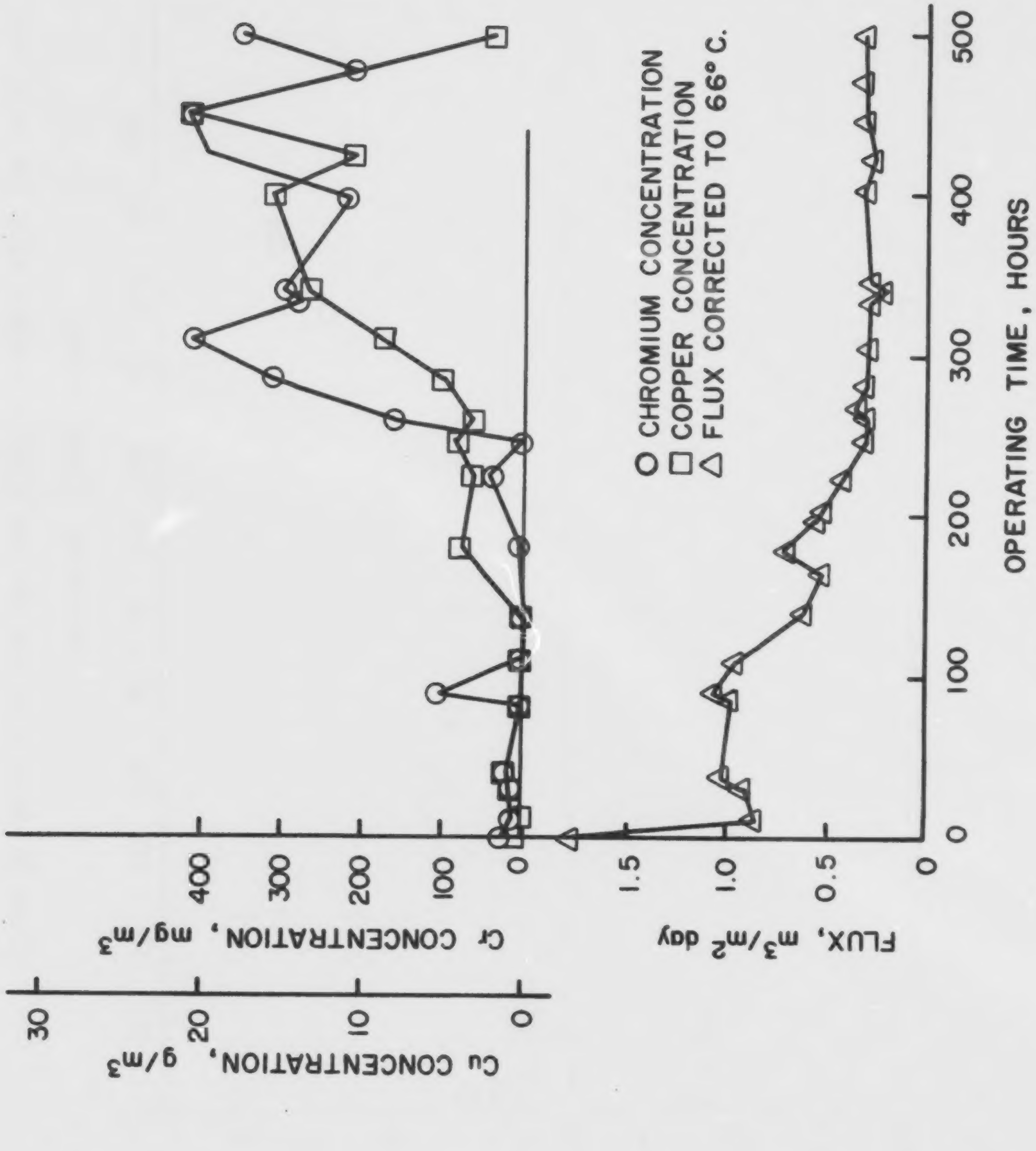


FIGURE 29 COPPER AND CHROMIUM EFFECT ON FLUX BEHAVIOR

TABLE 20. DYE ADDITIONS FOR REUSE TESTS

		Dye Used Based on % Fabric Weight	
Chemical	Dye Name	Test Dyeing	Normal Dyeing
2/09/77			
Direct dye	Superlitefast Yellow EFC	0.0420	0.0070
Direct dye	Superlitefast Blue 8GLN	0.0050	0.0500
Direct dye	Direct Fast Red 8BLN	0.0004	0.0030
Salt		25.0000	25.0000
1/22/76			
Direct dye	Superlitefast Blue 8GLN		0.2250
Direct dye	Superlitefast Yellow EFC		0.0020
Direct dye	Direct Fast Blue 4GL		0.0400
Salt		25.0000	25.0000
1/30/76			
Direct dye	Superlitefast Blue 8GLN		0.2250
Direct dye	Superlitefast Yellow EFC	0.0040	0.0020
Direct dye	Direct Fast Blue 4GL	0.0500	0.0400
Salt		25.0000	50.0000
3/11/77			
Direct dye	Diazol Light Orange 5JA	0.1500	0.0550
Direct dye	Direct Fast Red 8BLN	0.1250	0.0850
Direct dye	Superlitefast Blue 8GLN	0.0300	0.0110
Salt		50.0000	50.0000
3/04/77			
Direct dye	Diazol Light Orange 5JA	0.1350	0.0550
Direct dye	Direct Fast Red 8BLN	0.1500	0.0850
Direct dye	Superlitefast Blue 8GLN		0.0110
Salt		50.0000	50.0000
3/08/77			
Direct dye	Diazol Light Orange 5JA	0.1350	0.0550
Direct dye	Direct Fast Red 8BLN	0.1500	0.0850
Direct dye	Superlitefast Blue 8 GLN		0.0110
Salt		50.0000	50.0000
2/17/77			
Direct dye	Superlitefast Rubine WLKS	0.1000	0.4500
Direct dye	Superlitefast Yellow EFC	0.0100	0.0180
Salt		25.0000	50.0000

6.2 Operation on Dye Range

The skid was operated on the continuous dye range during the periods indicated in Table 21. The fluids in both washbox #1 and washbox #8 were selected for testing. In the interim period from April 20, 1977, and May 9, 1977, a new pump was installed in the skid due to the numerous difficulties encountered with the previous pump. The refurbished skid was returned on May 9 and was operated on the first dye washer (washbox #1) and on the soaper washer (washbox #8).

TABLE 21. SUMMARY OF TESTING OF HYPERFILTRATION ON DYE RANGE

Source (see Figure 4)	Membrane	Period	Hours	Samples	pH Adjustment
Washbox #1	SS Zr-PAA - 0.95 m^2	4/1-4/20	120	4001-4029	pH = 11 to pH∼7
	Replace Pump				
Washbox #1	Ceramic Zr-PAA - 0.012 m^2	5/9-5/23	220	4030-4070	pH = 11 to pH∼7
Washbox #8	SS Zr-PAA - 0.95 m^2	5/27-6/9	132	4071-4087	not adjusted

Conditions during operation on the fluid from washbox #1 are shown in Figures 30 and 31. Unexpected conditions resulted due to the pH adjustment and the periodic shade changes on the range. The skid was protected against running below about pH=2 (operator setting) and acetic acid was used to neutralize the feed to 7 < pH < 8 during operation, in anticipation of achieving optimum rejection. When shade changes occurred on the range, the washboxes were purged, thus interrupting the supply of feed to the skid. The feed would be processed normally until the low level cutoff interrupted the operation. The unit when stationary was such that acid added to the feed tank did not register a pH change since the pH indicator was located in the flow circuit, not in the tank. Acid would be continually added during the inoperative period. Upon restart of the range and restoration of feed, the operator would start the skid. Very quickly the excess acid would cause the pH to register below the acceptable limit (usually 2) and the unit would shut down. New fluid was added to the feed tank after draining the system and operation could be resumed.

The foregoing is detailed to suggest a cause for the flux behavior shown in Figure 31. The most probable explanation is that the membrane exposure to acid solutions "loosens" its structure allowing a temporary flux increase. We observe, during formation, that sudden pH steps, from 3 to 7 for example, result in a greater flux than a gradual transition of unit pH steps. Usually the rejection is observed to be lower also following large pH steps. One other explanation is that flux reducing multivalent metal ions may be released from the membrane during excursions to low pH. Separate laboratory tests fail to confirm that this mechanism is probable, at least with copper. Recovery of flux after exposure to copper is not readily done by lowering of pH alone.

It is somewhat speculative what level of flux may be attained without the intervening pH excursions, but we judge from the data of Figure 31 that 2 m^3/m^2-day is realistic at 65.5 C. However, the probable temperature of operation is only 45 C so that a correction to 1.25 m^3/m^2-day as a design flux is reasonable. All testing was performed between 4.8 and 5.2 x 10^6 N/m^2 (700 to 750 psi) and the permeate flux is expected to vary linearly with pressure.

The data indicated in Figure 29 for the atmospheric dye situation and that in Figure 31 compare the response of flux to the metal ion concentration. In the atmospheric beck dye case, the metals are part of the dye molecules and also may be present in the diluent. In the dye range case the source of chromium ions is not in the particular dyes used but may have been leaching from the stainless steel during low pH conditions. In any event the presence of comparable or greater metal ion concentration did not produce a comparable flux decline.

Following operation on the first washbox the unit was connected to waste from washbox #8, termed the "soaper" because it is the first washer after saturation with soap or detergent. The membrane

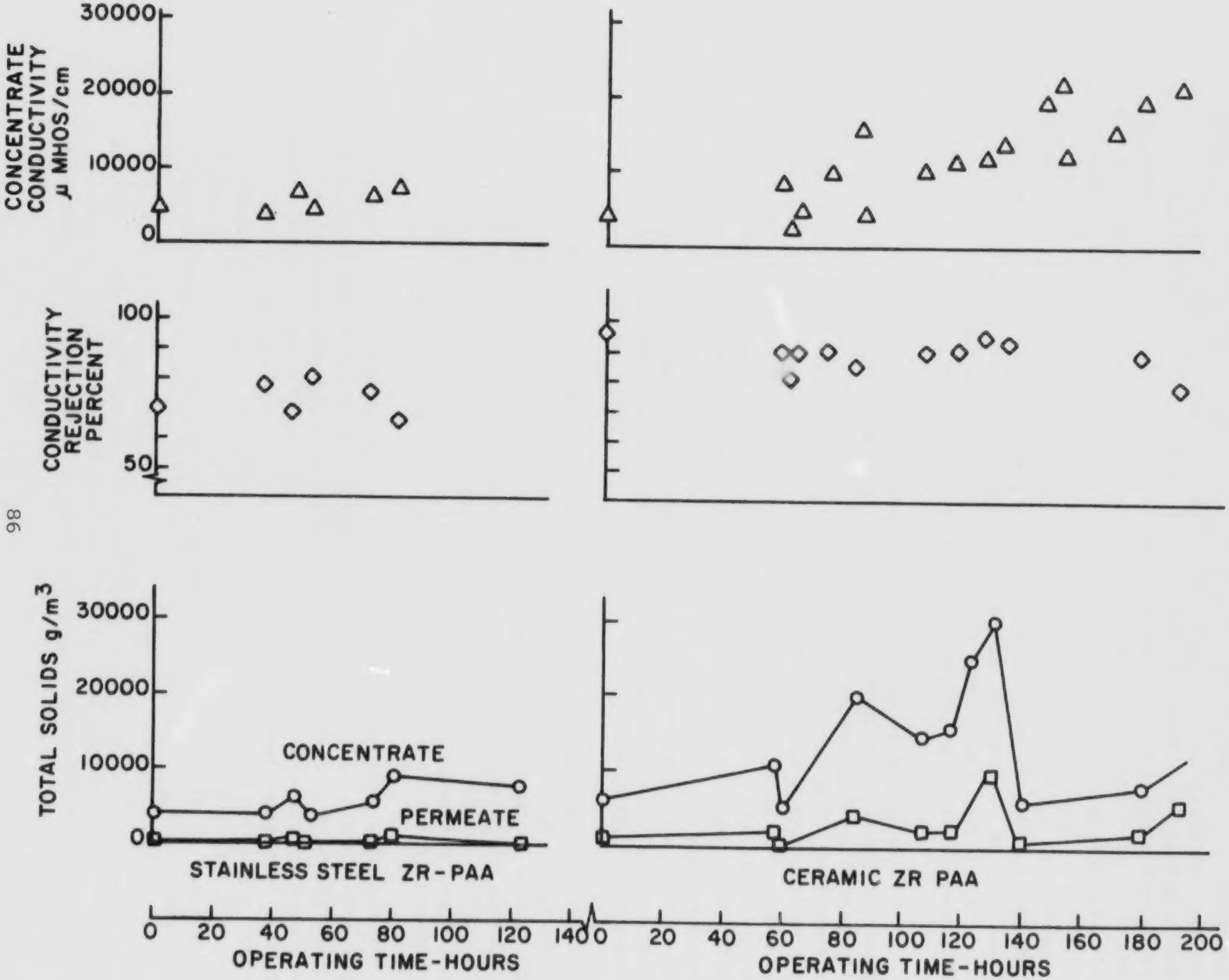


FIGURE 30 FIELD RESULTS - HYPERFILTRATION ON DYE WASHER

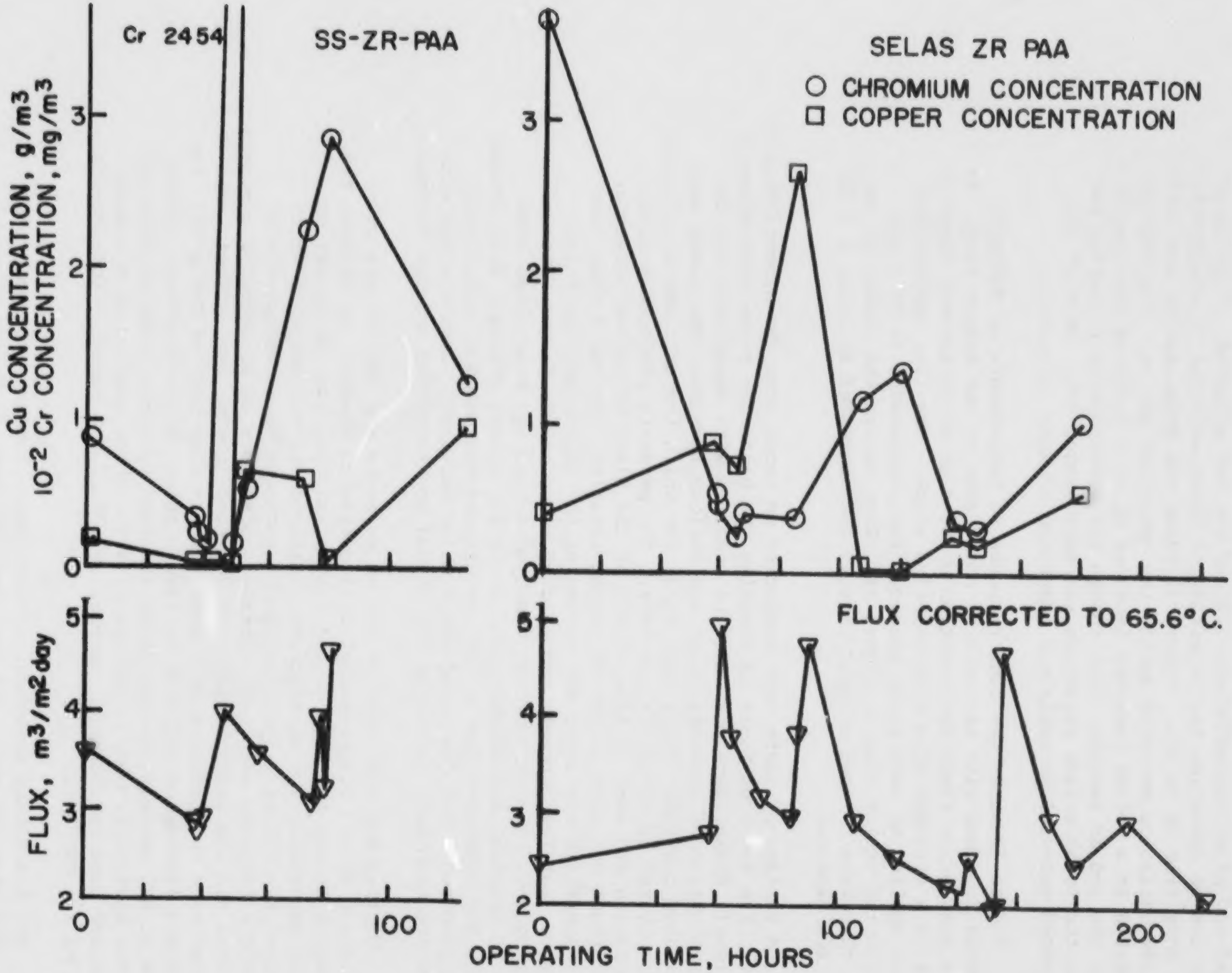


FIGURE 31 COPPER AND CHROMIUM COMPARISON TO FLUX

was operated for 132 hours from May 27, 1977, to June 9, 1977. The fluid had pH of approximately 3.8 and was not adjusted. Because of this low pH operation the rejection of ionic material (conductivity) was only from 30 to 50%. Figure 32 shows the conductivity and total solids variation observed during the operating period. The unit was operated at a volume recovery level of up to 0.9 during the testing. Near the end of testing, even though the conductivity rejection was low, the total solids rejection was approaching 90%. Most of the rejected material probably was comprised of soap carryover.

Figure 33 shows the flux response to temperature as darkened symbols together with the bulk of data taken on the soaper feed. As with most other feeds the relation of log flux to reciprocal temperature is a straight line with negative slope. The flux temperature trend applied to each point predicts the performance to 76 C and is plotted versus time in Figure 34. Even though the fluxes do vary 20% the overall trend is quite stable and fluxes of at least 4 m^3/m^2-day are expected.

A variety of tests were conducted on water from the hyperfiltration unit. The tests of Table 22 comprise the basis for reuse evaluation. Obviously these tests must also be combined with experience for the determination of reusability of the various streams. The tests were evaluated carefully for a navy shade for which the unit was pre-flushed and operated to yield 91% recovery. The permeate produced a slight coloration and some dulling effect on the blend of cotton/polyester. The effect was very slight on cotton material. In the filter test of concentrate the color was strong on the filter and the filter plugged, but the permeate produced no color on the filter material or plugging. The concentrate produced a bird egg blue (less than 10% of original shade) when used alone for a test dyeing. Test dyeing using the recovered dye in the concentrate augmented by additional dye produced a non-distorted color which was fast. Test dyeings with permeate water were conducted and showed no distortion and dye fastness.

Testing was also carried out on permeate and concentrate from operation on the soaper washer during several shades. As before, the permeate showed no color on the filter and this time no effect on cloth exposure. The concentrate contained colored material which stained the filter. Test dyeings on permeate were conducted with good dye fastness and no distortion. Some loss of brightening compared to soda ash and wetting agent was detected, though very slight. The concentrate and permeate were used for the soap test of Table 21. The permeate ribbon did not sink by five minutes, the concentrate ribbon sank in 8.5 seconds, and the soap standard solution produced sinking in two to five seconds. Foaming of eight-ounce samples in a blender produced foam volumes of: permeate - 473 ml (16 ounces); concentrate - 621 ml (21 ounces).

The laboratory personnel offered their summary judgments that
(1) the permeate water was adequate for reuse in dyeing or washing,
(2) some dye recovery was evident though the amount was too small to

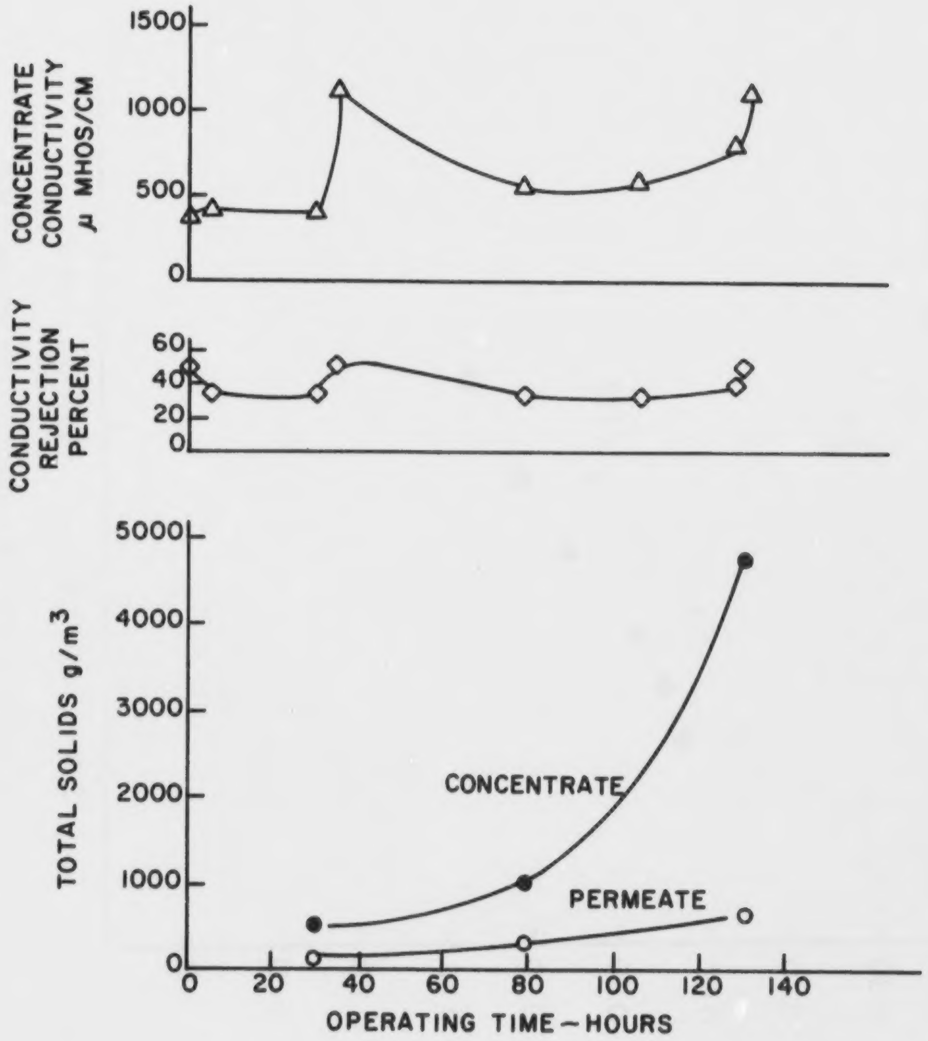


FIGURE 32 MEMBRANE EXPOSURE - SOAPER FEED ON DYE RANGE.

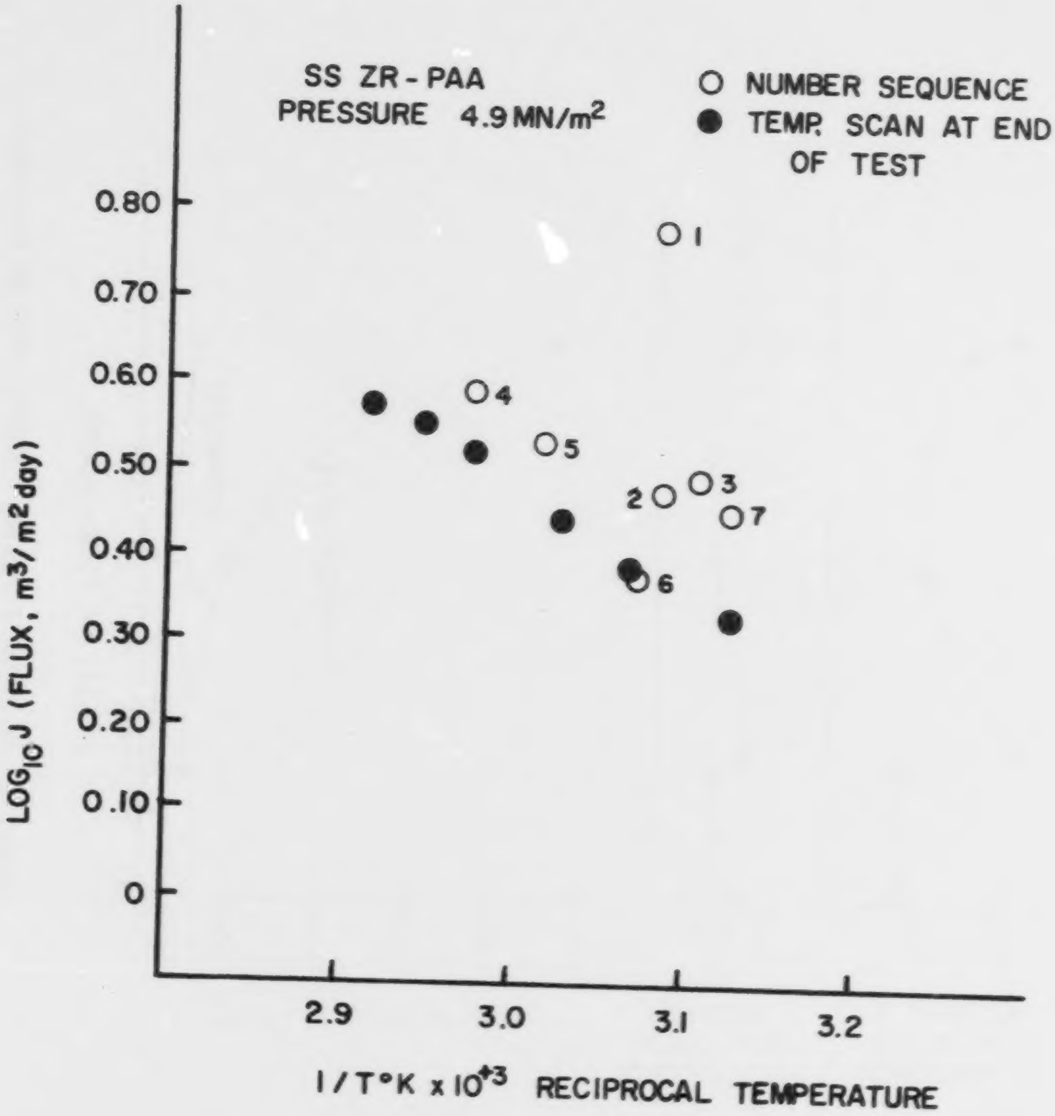


FIGURE 33 FLUX AND TEMPERATURE - SOAPER FEED ON DYE RANGE

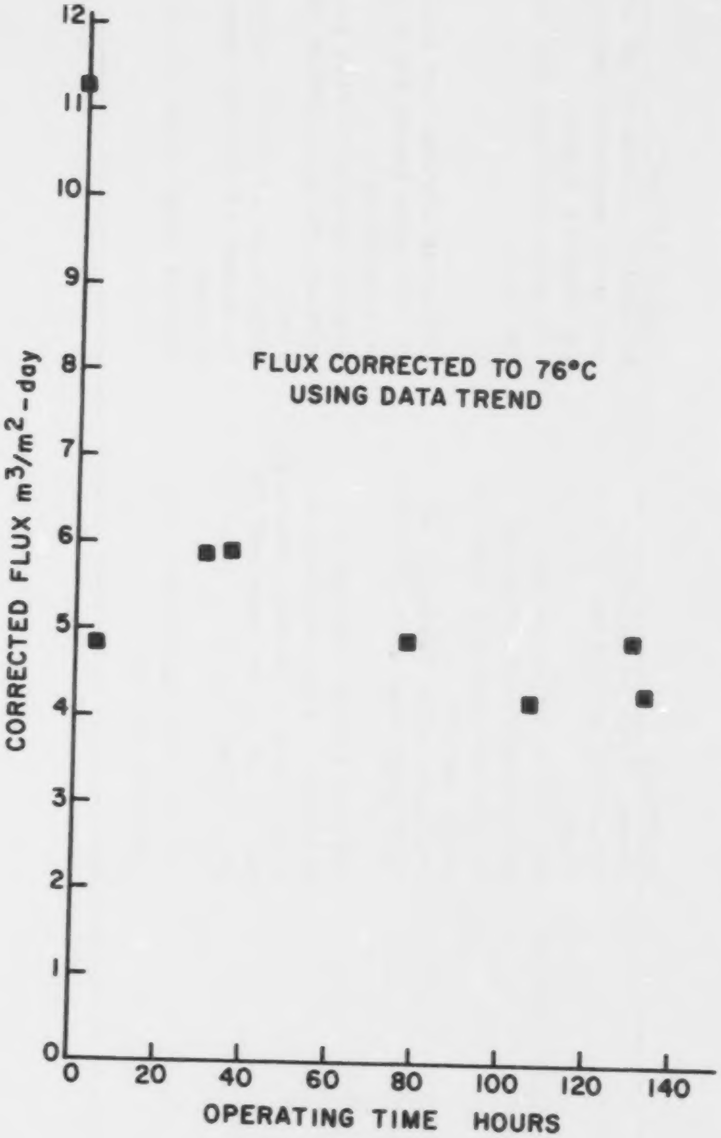


FIGURE 34 FLUX RESULTS - SOAPER FEED ON DYE RANGE

TABLE 22. DESCRIPTION OF DYE LABORATORY REUSE TESTING

Test	Procedure	Interpretation
Exposure	Expose cloth to solution, determine coloration of sample.	Excessive coloration of sample indicates excessive impurities for quality dyeing.
Test dyeing color match	Add dye to solution to determine amount required to produce standard shade on cloth sample.	Indicates potential for dye material recovery.
Fastness	Evaluate color fastness to both light and wash influence.	Indicates whether any reclaimed dye in the color match tests meets fastness standards.
Soap	Weighed ribbon exposed to solution. Time required to sink (cease floating) measured.	Soap or detergent will promote wetting and will reduce the time to sink.
Filter	Millipore filter examined for coloration following solution passage.	Coloration of filter proportional to amount of dye agglomerates present.
Foaming	Add solution to blender and operated blender.	Measure foam volume produced.

be economical, and (3) some soaper feed dragout was recovered, also too slight to be economical. We feel that the judgment of the economical is premature in that recovery to 90% means that the recovered chemicals are still volumetrically dilute. We believe the lab personnel judgment to be made on the basis of concentration, not on the rate of flow of recovered mass. One factor not considered in the dye recovery is that of the difficulty in segregating shades during normal operation involving shade changes perhaps every four to six hours. Since the soaper feed is not involved with this problem, its concentrate recovery should be easier technically. The buildup of color in recycled soaper concentrate could present a problem. Methods such as filtration, ultrafiltration, or simply blowdown could be used to separate or reduce offending color from recycled soaper feed if it becomes a problem.

6.3 Operation on Preparation Range Fluids

The hyperfiltration unit was operated on each of the three drains on the open-width preparation range. At the time of operation of the unit, the range was operated on polyester/cotton material having warp size composed of a starch and polyvinyl alcohol (PVA) mixture. This size contrasts with the formulation current with the energy survey and analysis of the drain. Otherwise the operation is similar, though the chemical additions are also milder. Overall the movable unit was on site from June 13, 1977, through August 26, 1977, and operated for over 360 hours combined on the three streams.

A minimum of information was gathered on the alternator (water washer) since pilot units are operating on such effluent and one full-scale recovery unit is in operation. However after forty-odd hours of operation, conditions were varied to provide data on the dependence of water flux on velocity and pressure. Figures 35 and 36 show the results obtained for high and moderate recovery situations. In the first part of Figure 35 four data observations at various velocity conditions confirm the expectation that flux varies with velocity to a power essentially 0.8 in turbulent flow. The single point falling off the trend is considered to be a non-equilibrium observation. During the operation on the range, it was common for the permeate flow to be unsteady. This unsteadiness is presumed to be due to a delicate balance between gravity and surface forces within the cavity of the module. Some other flow observations are much higher that could be consistent with all other observations at such conditions. The suspect data have been included even though they are felt to be observed in error.

In the situation where a high solids content of poorly diffusing solute is present to the extent that velocity effects are apparent, the flow resistance of the membrane is augmented by the resistance of the layer or rejected material. When the rejected

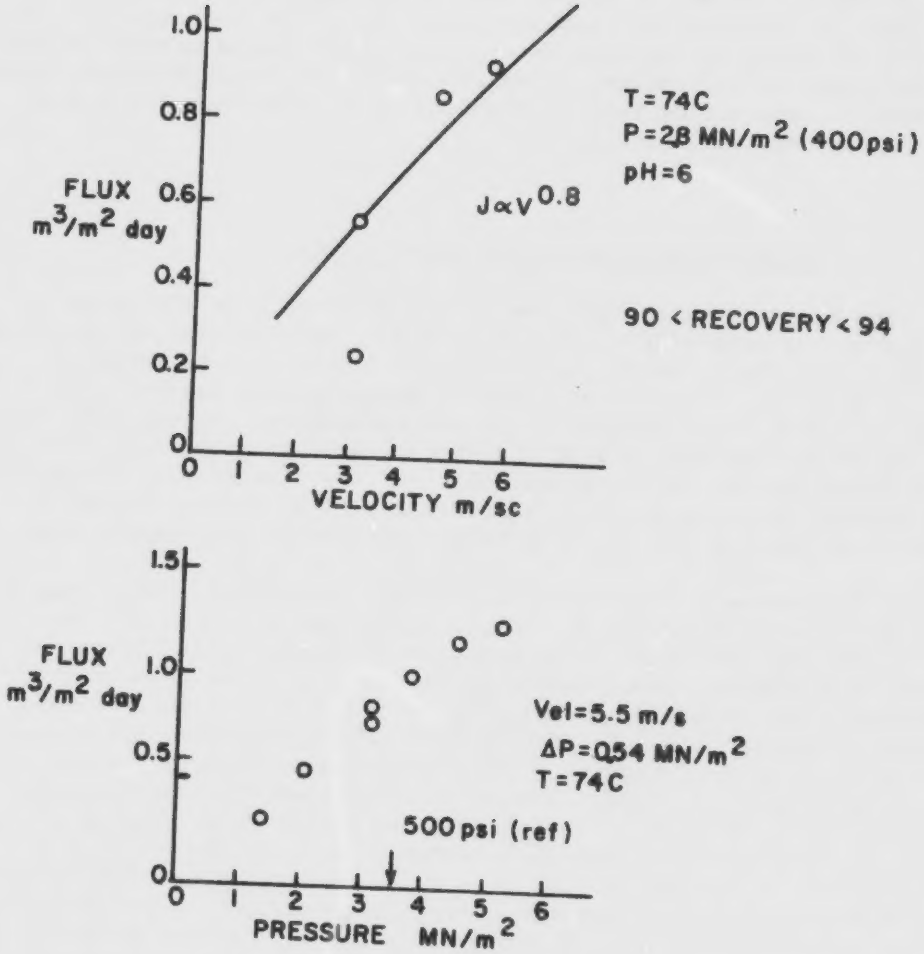


FIGURE 35 FIELD RESULTS - HYPERFILTRATION ON PREPARATION RANGE WATER - HIGH CONCENTRATION

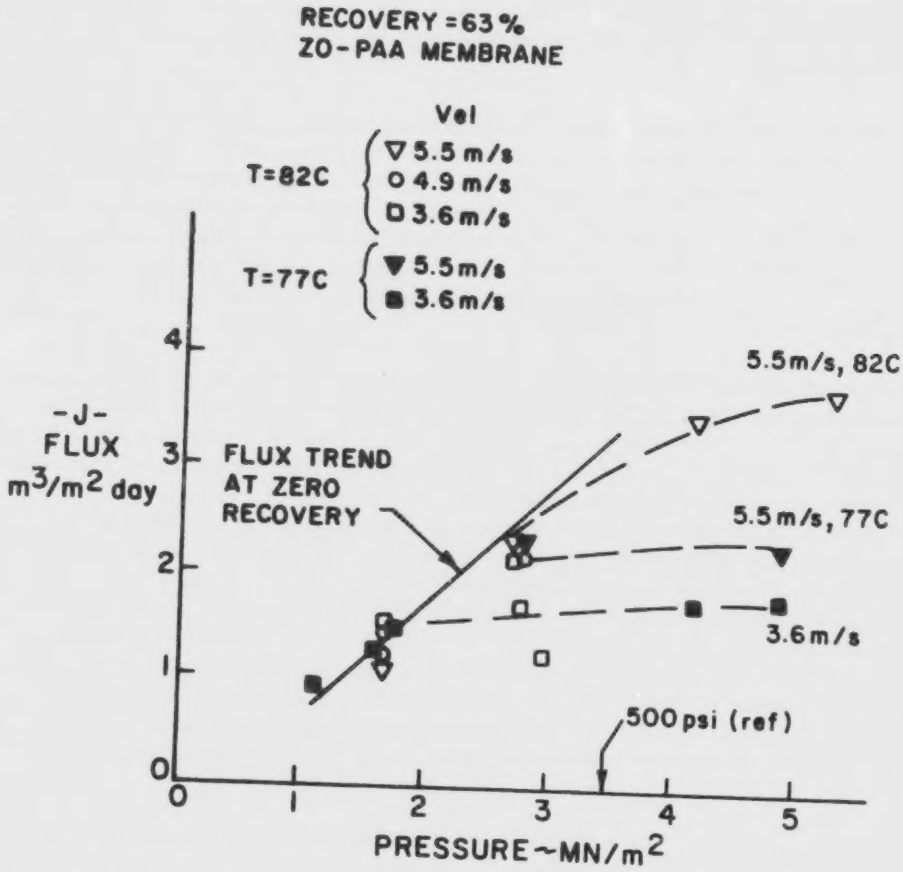


FIGURE 36 FIELD RESULTS - HYPERFILTRATION OF PREPARATION RANGE WATER WASHER - MODERATE CONCENTRATION

layer is sufficiently great in influence, the flux becomes "diffusion limited" and becomes independent of the membrane permeability. At such a condition there is a declining flow return as the pressure is increased indicated in the lower plot of Figure 35.

Initially the flux at 2.76 MN/m^2 (400 psi), 71 C, 5.1 m/sec was 1.89 x 10^{-5} m/s (40 GFD) and the unit was set up to achieve a particular recovery. It is not known to what recovery the data of Figure 35 correspond, but the levels of 90 to 94% are estimated to bracket the exact value. Water from the permeate was decreed qualified for reuse by plant personnel.

Normally one expects that (neglecting osmotic pressure for high molecular weight material) zero pressure should produce zero flow. However, the intercept in Figures 35 and 36 both extrapolate to zero flow with some 0.41 MN/m^2 (60 psi) applied. Since the pressure drop in the module was 0.54 MN/m^2, the average membrane pressure was less than the applied pressure at the inlet which is used as the independent variable. In light of the pressure drop, a 0.41 MN/m^2 offset is reasonable.

Water from the desize washer was used as feed for approximately 160 hours without a significant permeate flow reduciton. The flow had pH ≈ 11 to 12 and was not adjusted even though previous opinions favored pH control. Figure 37 shows the progression of both concentrate (feed to membrane) solution and the rejection data. A significant variation in raw feed to the unit was observed in the range from 1% to nearly 2% total solids for an average of 1.38% (13,800 mg/ℓ). The feed data are shown darkened in Figure 37. The rejection of conductivity was surprisingly high at the high pH level but did not result in elevated electrolyte as the rejection dropped quickly as the concentration increased. The rejection of total solids was high allowing concentration levels over 9% solids. At the 9% level the fluid viscosity was high enough that the feed to the pump could not be maintained fully and further concentration was not attempted.

Figure 38 shows the dependence of membrane flux on the fluid concentration. At the conditions of 4.13 MN/m^2 (600 psi), 71 C (160°F), and 5.2 m/s (17 ft/sec) velocity, the observed flux dropped from about 3.3 x 10^{-5} m/s (70 GFD) to about 0.5 x 10^{-5} m/s (10 GFD) at 9% solids corresponding to 88% volume recovery. Most of the data scatter appear to evolve from the compensation procedure used to adjust for the temperature effect. Points #5 and #7 were corrected more than 40 C and the temperature trends observed were not uniform. Despite the uncertainty in data interpretation the early and late data, separated by a hundred hours, do not indicate any membrane flux decline.

The effect of pressure and velocity on membrane flux was investigated briefly at one concentration. The results are shown in Figure 39. Data obtained at two velocities are shown together with the trend of the membrane as expected on water and on the desize washer

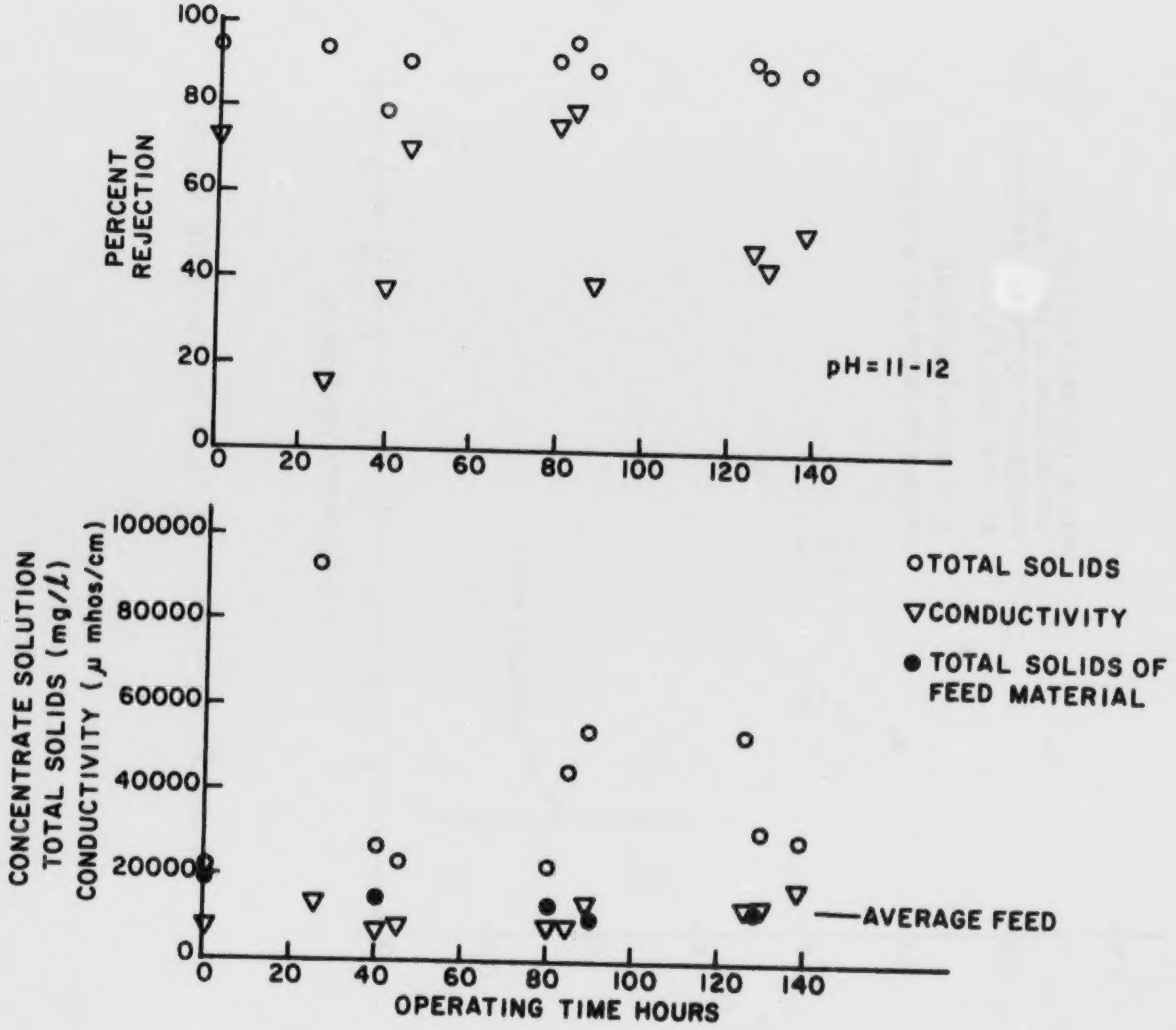


FIGURE 37 FIELD RESULTS - HYPERFILTRATION OF CHEMICAL DESIZE WASHER FLUID

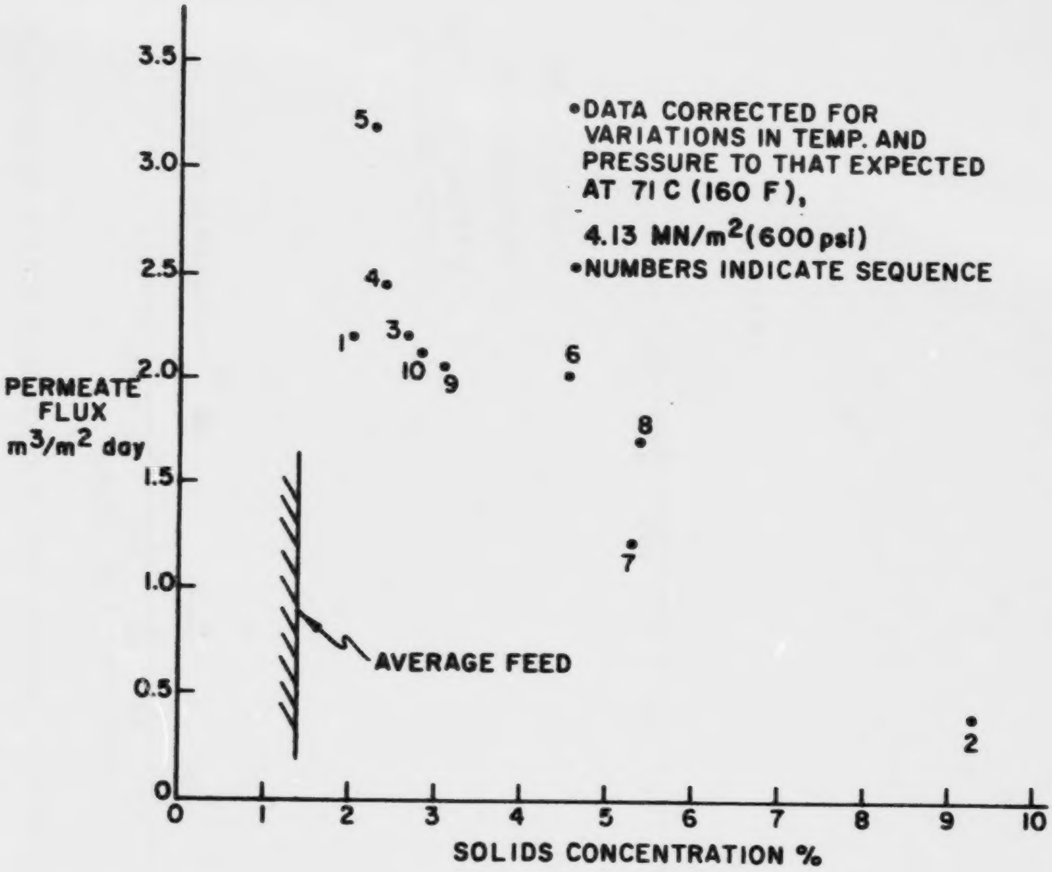


FIGURE 38 CHEMICAL DESIZE FLUID - FLUX VERSUS SOLIDS

ZO-PAA MEMBRANE
FLUX CORRECTED TO 71C(160F)
5.3 PERCENT SOLIDS

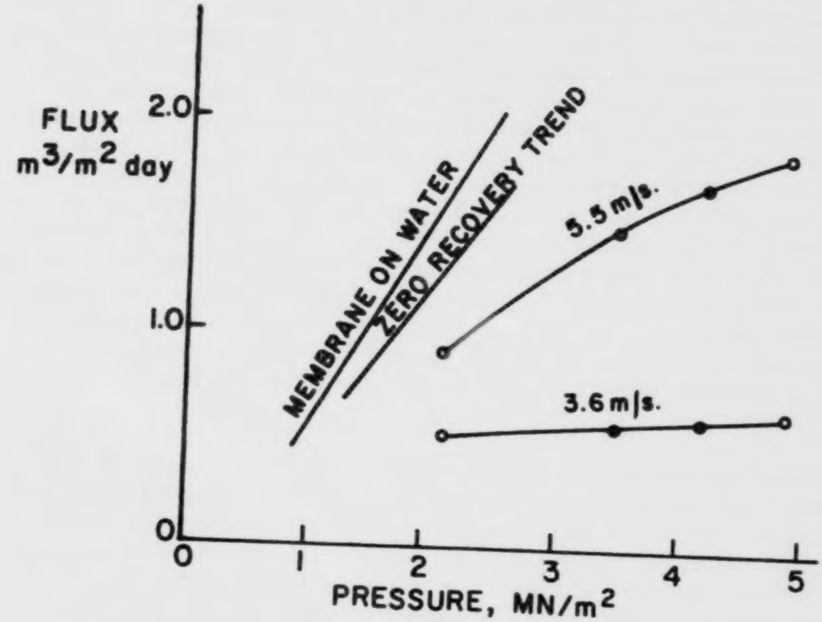


FIGURE 39 CHEMICAL DESIZE FLUID - FLUX VERSUS PRESSURE AND VELOCITY

at zero recovery. Clearly at the zero recovery a slight diffusion resistance is encountered and at the 5.3% solids level the resistance is significant. The indicated velocity effect is greater than anticipated. Usually flux varies with the 0.8 power of the velocity to a useful approximation. Although the viscosity of the fluid has not been determined, it is felt that the flow may be near or in laminar-to-turbulent transition. The data were run much cooler than 71 C so that the transition would be postponed to lower velocities at higher temperature.

Operation of the hyperfiltration unit was moved to the caustic washer. Even though the caustic water was not exposed to the membrane during the screening tests, the deisze washer experience was encouraging. Also the peroxide washer which was used in the screening tests does not have a drain but is counterflowed to the caustic section and thus was unavailable for processing. The operation was conducted for 100 hours without a significant change in permeate flux, although a slight increase was registered. At the end of the exposure period, some data on the effect of pressure, temperature, and velocity were determined. The data (Figure 40) show at 3.1 MN/m^2 that drops in flux occur as the velocity is changed from 5.1 to 3 m/s. The best interpretation is that the flux declines from 3.5×10^{-5} to 2.35×10^{-5} m/s (75 to 50 GFD) with the velocity variation. The single low value with a velocity of 5.1 m/s may be due to non-equilibrium in the relatively short accomodation period allowed. The flux thus interpreted varies nearly with $v^{+0.8}$ as predicted for diffusion phenomena. Two points were observed with quite high flux levels. Compared with the trend of the membarne on water, it appears that some observation difficulty may have been encountered. The lower plot of Figure 40 shows reasonable agreement between observations on the caustic fluid and that expected on water.

The data of Figure 40 are interpreted to indicate that at 87% volume recovery and below (lower concentration) the flux of permeate is essentially as it would be on water. This trend only holds for relatively high velocity operation; at lower velocities, and probably only at the higher concentrations, the flux declines about as $v^{+0.8}$. The data show nearly linear flux vs. pressure but in the velocity dependent region a declining return is predicted. It seems to be reasonable to expect an average flux of at least 2.35×10^{-5} m/s (50 GFD) and more probably 3.5×10^{-5} m/s (75 GFD) to be possible for a 90% recovery system.

Table 23 shows the results of analysis of spot samples from operation of hyperfiltration membranes on the caustic washer. The rejection of COD and total solids is high as expected. The presence of oil and grease and suspended material in the permeate may be due to intrusions into the sample container. Also the pH values noted are below 13 and are not considered accurate perhaps due to delay in measurement.

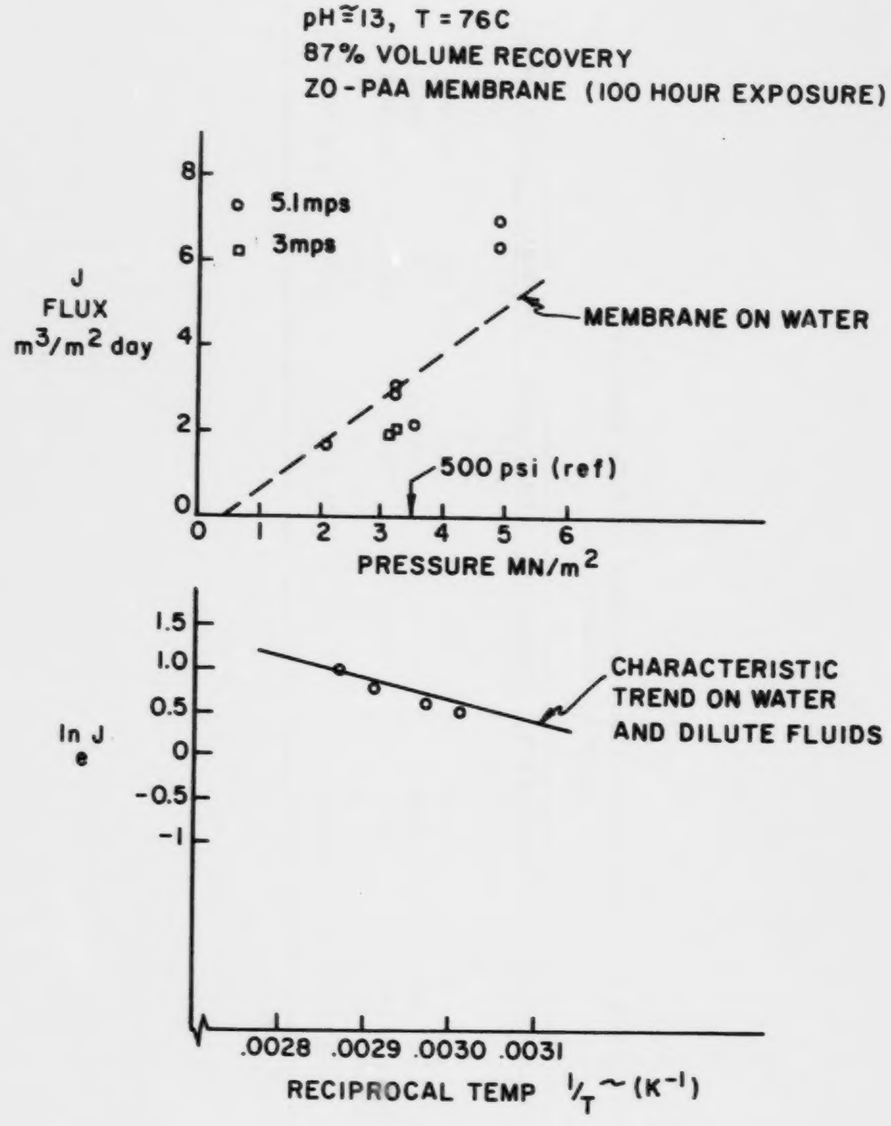


FIGURE 40 CAUSTIC WASHER FLUID - PARAMETRIC FLUX DEPENDENCE

TABLE 23. INDUSTRIAL PLANT ANALYSIS OF SPOT SAMPLES
(caustic washer)

Parameter	Permeate	Concentrate	Permeate	Concentrate	Permeate	Concentrate
Sample/Date	8/19	8/19	9/14	9/14	9/16	9/16
pH	12.6	12.7	12.5	12.6	11.7	11.3
Total Solids (mg/ℓ)	7300	21,900	6400	2100	13,400	92,900
Suspended Solids (mg/ℓ)	100	3400	0	200	0	6500
Volatile Solids (mg/ℓ)	5200	7500	4600	7500	6800	19,800
Oil and Grease (mg/ℓ)	0	0	0	0	100	0
COD (mg/ℓ)	5560	31,200	2124	21,744	4575	172,800

6.4 Ultrafiltration of Dye Range Fluids

The previously described ultrafiltration test unit was supplied with filtered feed from washer #1 of the dye range. The temperature was not controlled and tended to respond to process temperature depending on the rate of throughput. Figure 41 shows the results of operation. There was no noted effect of concentration in the range of 0 to 96% recovery which were run. The membranes were operated in the normal flow and pressure ranges except for the SS (stainless steel ZrO) dynamic membrane which normally operates at higher pressures and has lower permeability. The Abcor SWM ultrafilter was operated at pH ≈ 11 outside its intended pH range of up to 10.5 which may account for the drop in permeation rate noted. The SS module also experienced a flux decline while the Union Carbide module increased by a significant amount, not entirely due to temperature changes.

Table 24 shows the results of sample analysis for the rejection of the ultrafiltration membranes on the dye washer fluid. Except for the initial conditions, the dynamic membrane rejected in the highest amount. Materials present in the stream are sodium hydroxide, sodium hydrosulfite, and reduced dye. Figure 42 shows the relative light transmission recorded with each membrane including the dynamic hyperfiltration membrane. All membranes rejected the colored material well. The dye laboratory tests indicated sufficient color removal for reuse of each permeate.

TABLE 24. TOTAL SOLIDS REJECTION ON DYE WASHER

Date	Rec.	ABCOR-SWM	ZrO Dynamic	UC3NJR
6/7		19	27	28
6/8		45	55	33
6/10		16	35	16
6/13		30	43	21
6/24	50%	26	34	21

The membranes were next exposed to soaper washer effluent. Figure 43 shows the conditions and permeate results which were observed. No analysis was made supporting the activity except the reuse evaluation. Reuse of the water was satisfatory and there was no concentration of surfactant observed. The Union Carbide membrane flux diminished somewhat compared to operation on the dye washer. Both other membranes registered increases in flux - the dynamic membrane because of the temperature increase, and the Abcor membrane presumably because of relief from the previous fluid conditions. The soaper washer produces apparently ideal conditions for all membranes applied to it. The mild acetic acid and oxidant together with extremely dilute trash content all presumed to contribute to this situation.

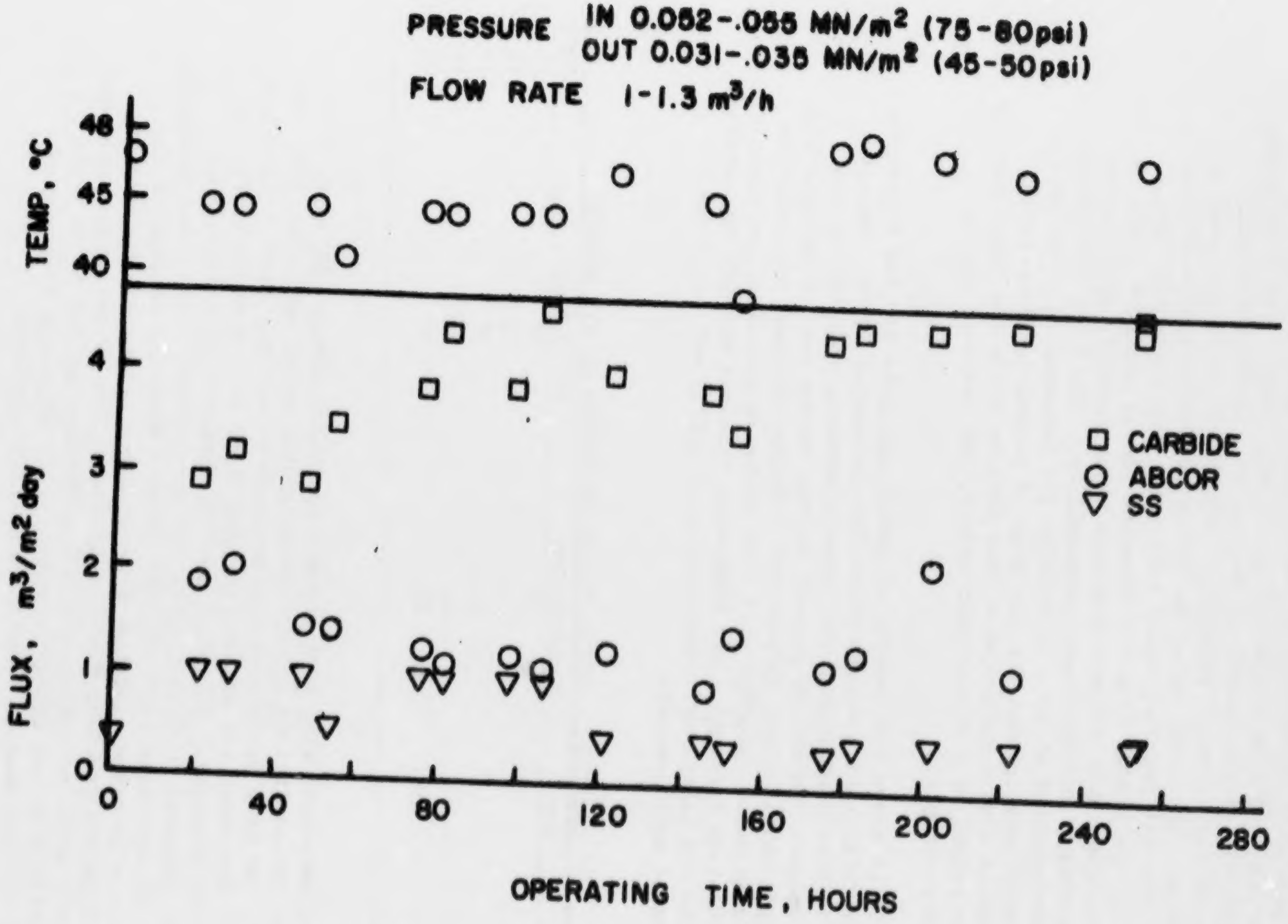


FIGURE 41 FIELD RESULTS - ULTRAFILTRATION ON DYE WASHER FLUID

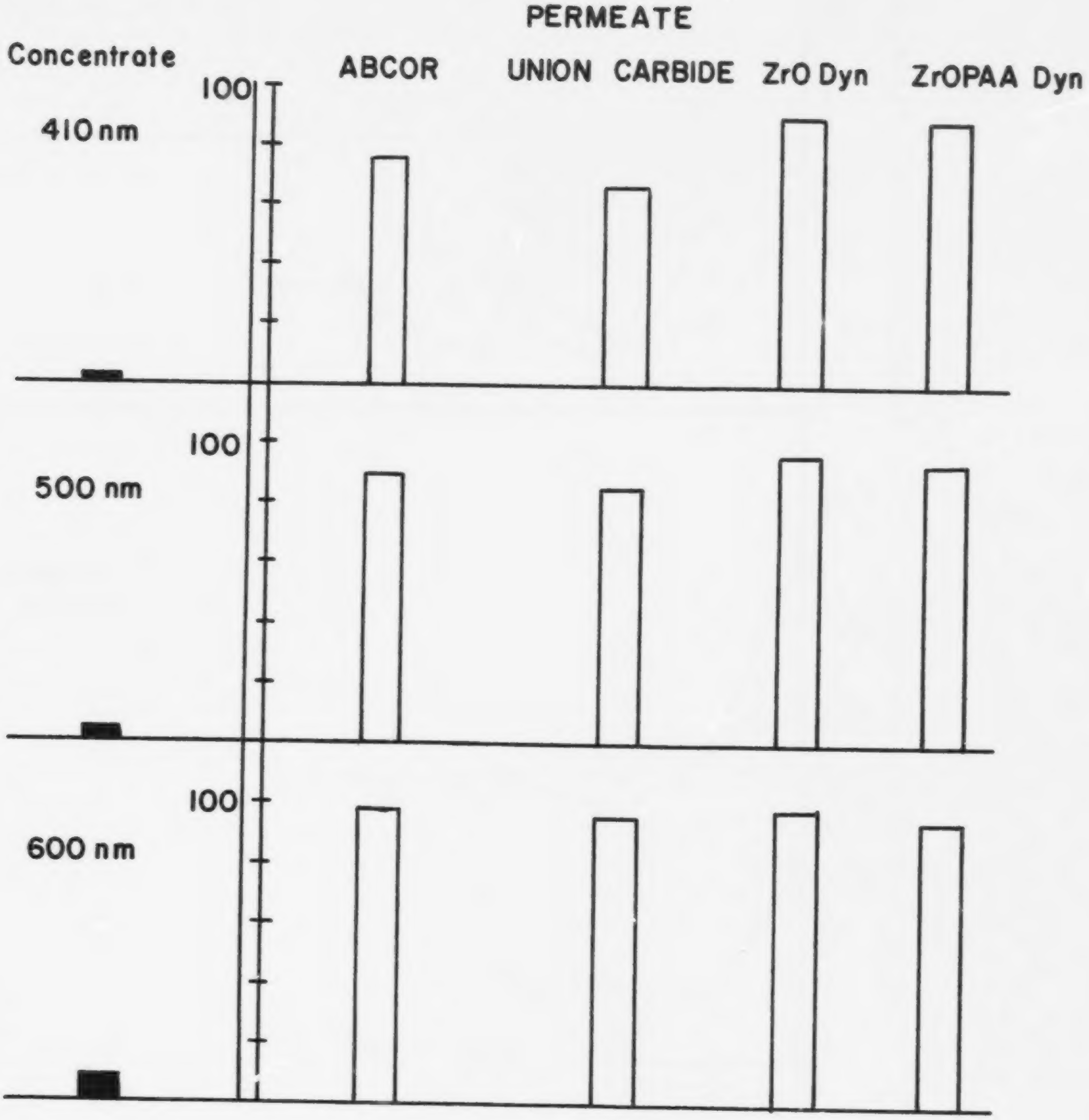


FIGURE 42 RELATIVE LIGHT TRANSMISSION - MEMBRANES ON DYE WASHER

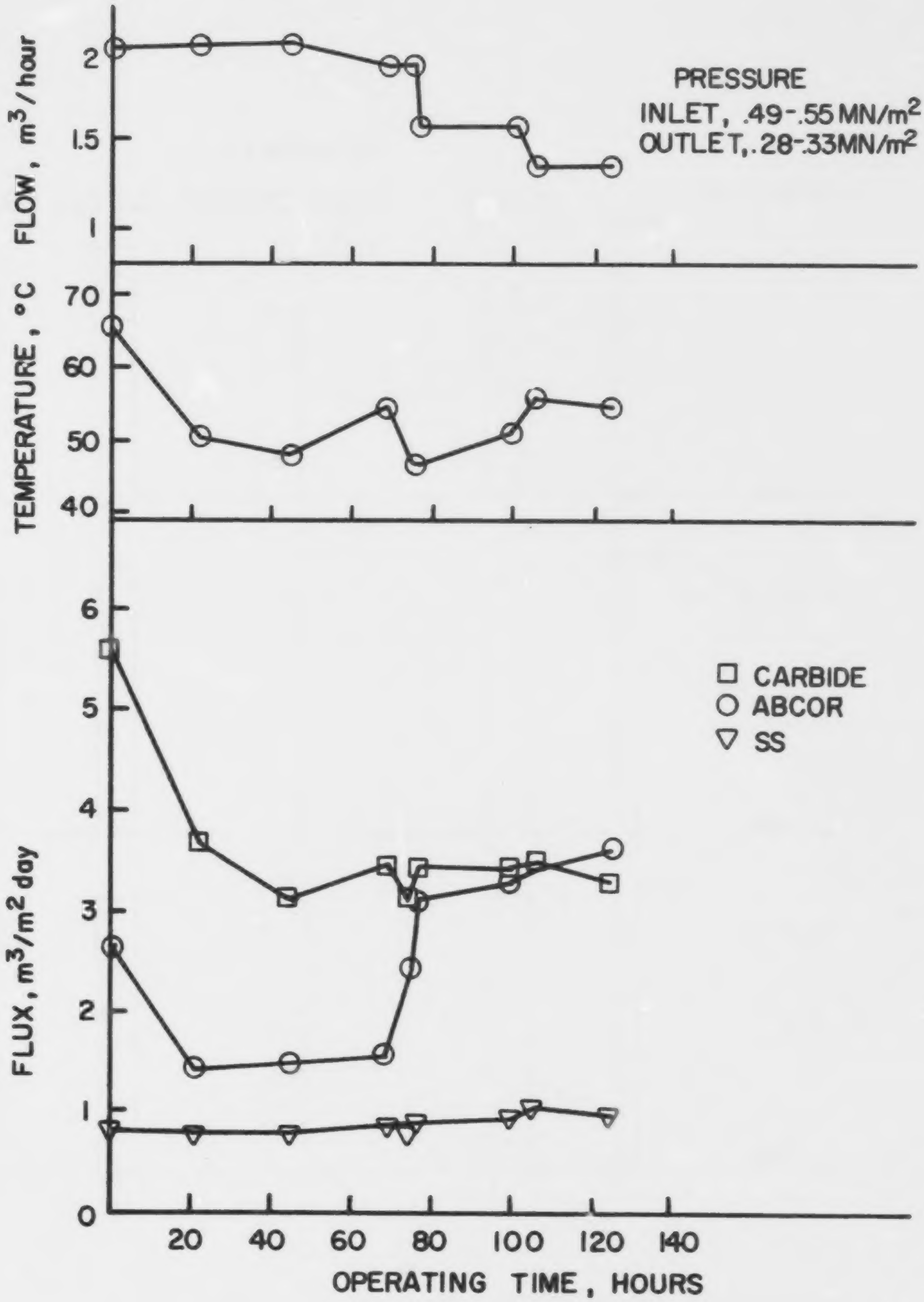


FIGURE 43 FIELD RESULTS - ULTRAFILTRATION ON SOAPER WASHER DYE RANGE FLUID

The ultrafiltration skid followed the hyperfiltration skid to the preparation range where membranes were applied to fluids in the first two washers. In contrast to the operation of the hyperfiltration membrane on the alternator (water desize) washer, only slight velocity dependence to the flux was observed. Part of the reason may be that, at the low operating temperature, the flow may be laminar due to the increase in viscosity with decreasing temperature. In laminar flow the effect of velocity on diffusion resistance is much less pronounced than in turbulent flow. Because of this low temperature condition the data of Figure 44 may be significant underestimate of the permeate rates which would occur at 80 C (expected observation). The data obtained for the hyperfiltration membrane shown in an earlier section should be essentially identical to that obtained for ultrafiltration at similar conditions. However, the flux (hot fluid) for hyperfiltration was higher.

Rejection of total solids (average of two determinations) for the three membranes operated on water washer fluids was: Abcor - 48%, Union Carbide - 57%, Zro dynamic - 71%. Despite the relatively low values all permeate water was found to be satisfactory for reuse by laboratory tests. Laboratory analysis performed by the cooperating industrial plant of the relative contents of the permeate samples are shown in Table 25.

TABLE 25. PREPARATION RANGE WATER WASHER: COMPARISON OF ULTRAFILTRATION PERMEATES

Item*	ABCOR Permeate	ZrO Dynamic Permeate	UC3NJR Permeate
COD	2446	1960	1599
Suspended Solids	0	100	200
Total Solids	3100	1700	2400
Volatile Solids	1200	800	800
Oils and grease	0	0	0
pH	6.0	7.7	6.4

* Units in ppm except pH which is unitless.

Samples 8/8/1977.

The skid operation was moved to the chemical desize washer. Only the Union Carbide membrane was used because of the high pH in excess of the recommended level of Abcor operation and the low total flow rates produced by the SS dynamic membrane. The data are shown in Figure 45. After a brief period the flux dropped to the line shown in the figure where it held constant for about 100 hours. Two complete concentration runs were performed and the operation was performed while attempting to maintain an elevated temperature. The data taken are sketchy, but are presented in the interest of completeness. As in the water desize washer, the ultrafiltration results for flux are less than those measured for hyperfiltration. The region of concentration

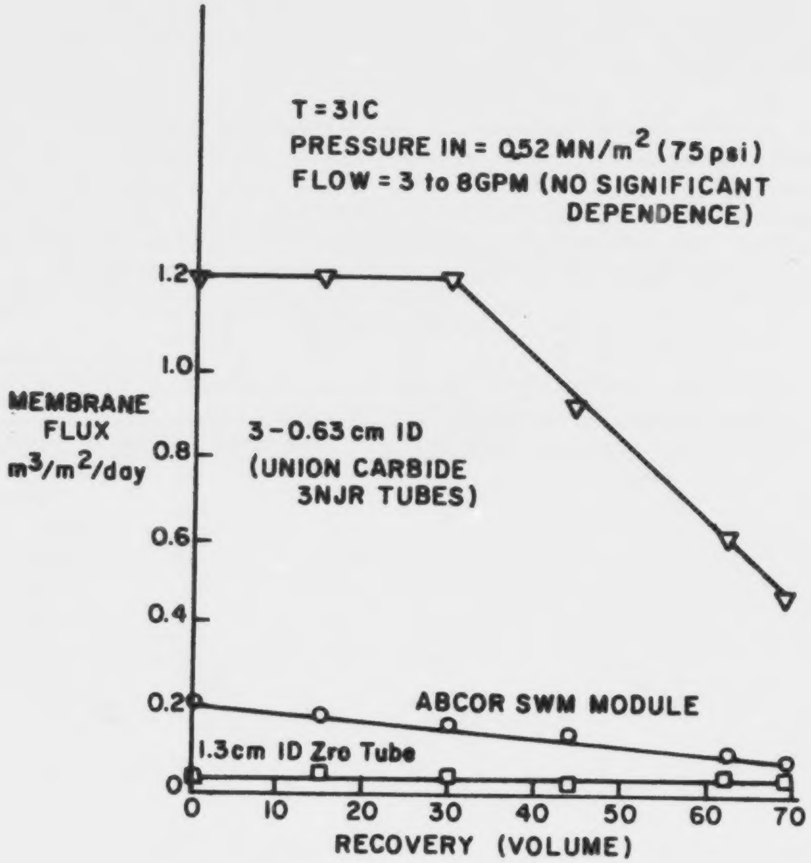


FIGURE 44 FIELD RESULTS - ULTRAFILTRATION OF WATER DESIZE FLUID

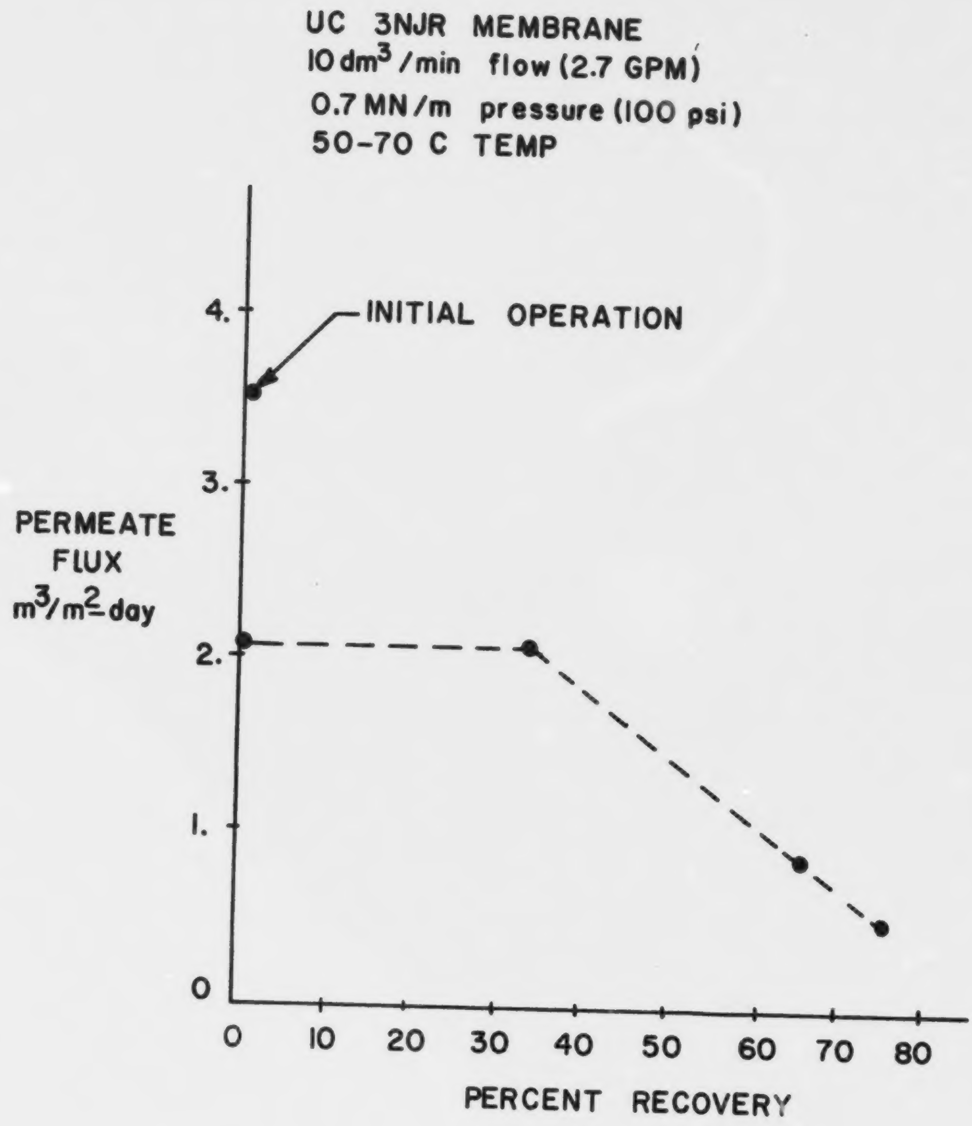


FIGURE 45 FIELD RESULTS - ULTRAFILTRATION OF CHEMICAL DESIZE FLUID

below about 35% recovery is indicated to be membrane permeability limited. At higher recovery levels, the concentrated material adjacent to the membrane increases the resistance to flow and the steadily decreasing flux.

7.0 ECONOMIC ESTIMATES

The following section describes an effort to forecast the general level of costs associated with the application of pressure driven membranes. There are acknowledged weaknesses in the information and its applicability will not be uniform to all sites in the industry. There is a fundamental procedure which has been followed in achieving the estimates made herein. First, the field data have been used to arrive at a design of a membrane unit which will achieve a stated recovery goal. The designs account for pressure drop and where possible arrange modules to form a tapered system. In the tapered system the velocity is maintained within a certain range by dividing the flow into an appropriate number of parallel elements. The designs of hyperfiltration systems always optimize at the lowest velocity comensurate with high rejection. Usually the velocity is decreed rather than designed. In ultrafiltration (high solids cases) applications there is frequently a balance between cost of membrane and cost of pumping. At low velocity the pumping cost is diminished but the flux decreases causing an increased membrane size. In the following designs the optimum has been sought for such cases and the velocity or flow is stated for situations where no optimum occurs.

7.1 Individual Designs

7.1.1 Water Washer on Preparation Range 151 dm^3/min (40 GPM, 75% recovery)

Abcor ultrafiltration modules have been arranged as (number in parallel x number in each leg) accordingly to the following schedule of segments: (8 x 25)+(5 x 20)+(3 x 37). The flux data at 0.48 MN/m^2 (70 psi) have been adjusted in proportion to pressure. Three repressurizations have been required. It is believed that a significant design improvement would be realized by allowing higher pressure to be utilized. The membrane area could be reduced considerably and the number of pumps decreased. The flux schedule shown below has been used with an assumed value of 3.44 m^2 (37 ft^2) of area per module.

% recovery	flux m^3/m^2-day	(GFD)
0	0.204	(5)
30	0.163	(4)
50	0.122	(3)
75	0.081	(2)

Pressure drops proportional to the square of flow have been used with $\Delta P = 7\ kN/m^2$ (1 psi) at 0.0011 m^3/min (3 GPM) flow rate. Flow rates are maintained between 0.0011 and 0.016 m^3/min for the design stated. Power consumption of 45 kw is estimated.

Union Carbide ultrafiltration modules in 46.5 m^2 (500 ft^2) elements have been employed. These packages have been operated with an assumed recirculation flow of 0.0038 m^3/min (1 GPM) to each of the 1910 elements. The following fluxes per module have been used in agreement with the data taken.

Module	Flux m^3/m^2 day	(GFD)
1	1.22	30
2	0.896	22
3	0.652	16
4	0.469	11.5
5	0.367	9

The power consumption of each module is estimated at 28 kw, for a total of 140 kw.

ZrO membrane performance was measured at low pressure of 0.48 MN/m^2 (70 psi) which has been assumed to be scaled proportional to a pressure of 4.8 MN/m^2 to yield a flux of 0.406 m^3/m^2-day (10 GFD). A single pass system would require at least 4015 m^2 (43,200 ft^2) of area and will require a minimum of 40 kw of pump power.

The ZrO membrane data suggests a region from 0 to 50% recovery of constant permeability at 3.3 m/s greater velocity; $J = 1.8\ m^3/m^2$-day (44 GFD) at 1.66 MN/m^2 (240 psi). From 50 to 75% recovery the data suggests $J = J_o\ (v/v_o)**0.8$ (double asterisk is Fortran symbology for raised to power 0.8). Here $J_o = 1.63\ m^3/m^2$-day (40 GFD) at $V_o = 3.3$ m/sec (11 fps). A pressure drop of 9100 N/m^2 per m of length at 3.3 m/sec velocity has been used. The design resulting is expressed as (number of parallel elements x length of element) in the groupings (5 x 36.6 m) + (3 x 49 m) + (2 x 527 m) + (1 x 152 m). The first two groups reduce the flow to the 50% recovery work and the last two provide the final concentration. The overall results is 65 m^2 (700 ft^2) and membrane area and 40 kw pump power required.

7.1.2 Chemical Desize Washer (0.151 m^3/min (400 GPM) 80% recovery)

The Union Carbide data taken are not conclusive but based on the best interpretation the following design is made (6 m/s velocity).

Module	Flux m^3/m^2 day	(GFD)	% Recovery
1	1.83	(45)	45
2	1.02	(25)	62
3	0.49	(12)	70

Here 3 modules can be used to achieve 70% recovery of feed water as permeate.

The ZrO-PAA membrane data projected to 82 C and 3.6 m/s velocity are as follows.

% Recovery	Flux (average) m^3/m^2 day	(GFD)
0 to 40	2.04	50
40 to 60	1.69	41.5
60 to 70	1.43	35
70 to 75	1.25	30.6
75 to 80	1.00	24.6

Using these flux data permits estimation of 79 m^2 (750 ft^2) of membrane area and three pressurizations using a power of 50 kW. It would be attractive to pursue a lower velocity design to allow less pumping.

7.1.3 Caustic Washer (0.151 m^3/min (40 GPM) @ 90% recovery)

Only the ZrO-PAA membrane was operated on this feed and at the elevated pH the results are not expected to be due to the second layer (PAA). The data suggest little effect of velocity and that the flux J is 9.7 x 10^{-7} m/N-day times the pressure (e.g. 6.72 m^3/m^2-day at 6.94 MN/m^2). A system having a velocity about 3 m/s velocity requires two pumps and has area of 36.5 m^2 (393 ft^2). A lower velocity could possible be adopted to eliminate one of the pumps but no data were taken in the 2 m/s range to justify such a design. A power requirement of 47 kW is estimated.

7.1.4 Dye Washer #1 (0.163 m^3/min (43.2 GPM) @ 90% recovery)

The Abcor unit showed 1.01 m^3/m^2-day (25 GFD) flux production, and pressure drop is not high in this case, so a simple estimate of 60 modules results. Power of 7.5 kW is sufficient for pumping.

The Carbide membrane produced 4 m^3/m^2-day (100 GFD) on this feed such that one module will essentially recover 90%. Power of 28 kW is required.

7.1.5 Soaper Washer on Dye Range (0.163 m^3/min (43.2 GPM) @ 90% recovery)

The Abcor module produced 3.3 m^3/m^2-day (81 GFD) at expected operating conditions. An assembly of 19 modules requiring 3.5 kW power is judged adequate.

The Carbide unit also produced 3.3 m^3/m^2-day flux but is expected to produce double this at operating pressures of the design. A single 500 ft^2 module is only operating to 70% of its capacity. Power of 28 kW is required.

The ZrO membrane flux adjusted for pressure effects in operating compared to testing is 8 m^3/m^2 day so that 26 m^2 (280 ft^2) of membrane is estimated. Power of 43 kW is also estimated.

The ZrO-PAA membrane produced a flux of 4.2 m^3/m^2-day (103 GFD). A membrane having 51 m^2 (595 ft^2) is anticipated. Power required is 43 kW. A higher recovery fraction could be achieved with this membrane with the possibility of retrieving a portion of the $65 per day soap cost.

7.1.6 Atmospheric Dye Becks (0.319 m^3/min (83 GPM) 95% recovery)

The flux data on the atmospheric dye becks showed about 200 hours of operation at high flux followed by a severe flux decline to 20% of the initial value. The drastic nature of the decline leads to the probability that there is an element of feed which causes the decline which may be avoided. Therefore, two designs are advanced, one using the low flux and the other using the relatively vulnerable high flux. The high flux case is only meaningful if a problem elimination or cleaning methodology is worked out.

The low flux is about 0.306 m^3/m^2-day (8 GFD) while the high flux is 1.63 (40 GFD). The resulting designs at 2.1 m/sec velocity require 1352 m^2 (14,250 ft^2) and 265 m^2 (2850 ft^2) respectively. Operating power of 91 kW is estimated, though the high flux design will require less.

7.2 Costs of Systems

The following groundrules have been used in the process of evaluating expected costs. Abcor has provided a budgetary estimate for the systems described, including motors, rudimentary controls, and mounted on an equipment skid. The Union Carbide system cost has been estimated by the authors at $50,000 per module and it is presumed that this would include drives and rudimentary controls. The ZrO and ZrO-PAA systems costs have been estimated at $1290 per m^2 ($120 ft^2) except for very large units of $1070 per/$m^2$. This estimate has been based on tube prices in appropriate quantities ($70 per ft^2), the cost of assembly for heat exchangers ($10 per ft^2), the expected cost of membrane application to assembled modules ($5 per ft^2), costs of pump stations with controls of $10,000 flat costs, and a factor of about 25% for profit and indirect costs.

Annual replacement costs for Abcor units are estimated based on two year expected life and represent about 12% of initial cost. Replacement of tubes for the tubular membranes is expected to cost 3% of the purchase price, though little data exist to support the estimate. Abcor estimates $500 to $2500 annual cost for cleaning. The tubular membranes likely have a cleaning requirement which has not been estimated. Operating costs due to pump power have been calculated with $.02 kw hour on a 6000 hour year basis (250 days/yr).

Prefiltration has shown itself to be a major concern with spiral membranes. An amount from $2500 to $5500 annually has been added to Abcor's estimate to account for this cost. No similar estimate is appropriate for the tubular membranes.

Water and energy savings have been estimated on a 6000 hour per year estimate. Water costs of $0.055 per m^3 (25¢ per k gal) and energy costs of $3.00 per MBtu have been used. These figures result from an informal survey of local industry and are arbitrarily selected because of the rapid changes. Only energy added above 40.5 C (105°F) has been claimed as conserved to account for energy recovery in the plant. This is with the single exception of the beck recovery in which all energy relative to 18 C (65°F) is claimed as savings.

For all systems the cost of installation has not been added. The authors feel (with little data to cite) that historic estimates of installation ratios (60 to 100%) are excessive for the compact equipment with relatively high costs that membrane systems represent. Many of the small systems described herein may well be installed for under 20% of the purchase price. The layout of a user's facility, his relative local power accessibility, and other factors will play a prominent role in the installation costs. Therefore no installation costs are included.

No operator costs have been assigned to the systems. All systems can be made to fail safe with allowance for the user's range or facility to continue normal operation. Thus no operator is required and malfunctions may be treated by the vendor or perhaps by the plant's maintenance department.

In a naive way, the cost of yearly amortization has been estimated to allow a crude estimate of the net annual cost or savings for a prototype installation. The present worth factor of 4.35 has been used to amortize capital costs at a 10% interest rate over six years. That is, the capital cost divided by 4.36 is taken as a yearly cost of capital. No effect of tax is evaluated.

7.3 Results of Economic Survey

Following the groundrules mentioned in the preceding section, each of the designs has been evaluated. Tables 26, 27, and 28 show the results

TABLE 26. RESULTS OF ECONOMIC ANALYSIS FOR PREPARATION RANGE

Water Washer - Preparation Range

System	Capital Costs	Cost of Yearly Amortization	Annual Replacement Costs	Annual Operating Costs	Annual Water a) Savings	Annual Energy b) Savings	Net Annual (Cost) Savings
Abcor	$460,000	$105,500	$60,000	$12,900	$2,700	$20,250	($155,000)
UC/GC	250,000	57,300	7,500	16,800	2,700	20,250	(58,650)
ZrO	432,000	98,600	12,900	4,000	2,700	20,250	(92,550)
ZrO-PAA	84,000	19,300	2,500	3,480	2,700	20,250	(2,330)

Chemical Desize Washer - Preparation Range

System	Capital Costs	Cost of Yearly Amortization	Annual Replacement Costs	Annual Operating Costs	Annual Water a) Savings	Annual Energy b) Savings	Net Annual (Cost) Savings
UC/GC	$150,000	$34,400	$4,500	$10,100	$2,538	$21,437	($25,025)
ZrO-PAA	120,000	27,500	3,600	6,090	2,900	24,500	(9,790)

Caustic Washer - Preparation Range

System	Capital Costs	Cost of Yearly Amortization	Annual Replacement Costs	Annual Operating Costs	Annual Water a) Savings	Annual Energy b) Savings	Net Annual (Cost) Savings
ZrO-PAA	$47,000	$10,800	$1,400	$5,220	$3,200	$27,500	$13,280

a) Savings @ 25¢/kgal
b) Basis of 105 F to 180 F heating saved

TABLE 27. RESULTS OF ECONOMIC ANALYSIS FOR DYE RANGE

Dye Range, 1st Washer

System	Capital Costs	Cost of Yearly Amortization	Annual Replacement Costs	Annual Operating Cost	Annual Water a) Savings	Annual Energy b) Savings	Net Annual (Cost) Savings
Abcor	$ 90,000	$20,600	$10,500	$4,400	$3,500	$3,000	$(29,000)
CU/GC	50,000	11,500	1,500	3,357	$3,500	3,000	(9,800)
ZrO	134,400	30,826	4,020	3,800	$3,500	3,000	(32,145)
ZrO-PAA	223,920	51,360	6,720	3,800	$3,500	3,000	(55,380)

Dye Range, Soap Washer

System	Capital Costs	Cost of Yearly Amortization	Annual Replacement Costs	Annual Operating Cost	Annual Water a) Savings	Annual Energy b) Savings	Net Annual (Cost) Savings
Abcor	$50,000	$11,500	$10,500	$3,000	$3,500	$22,600	$ 1,100
CU/GC	50,000	11,500	1,500	3,360	3,500	22,600	9,700
ZrO	33,600	7,700	1,000	3,800	3,500	22,600	13,600
ZrO-PAA	65,400	15,000	1,900	3,800	3,500	22,600	5,400

a) Savings @ 25¢/kgal
b) Basis of 105 F

TABLE 28. RESULTS OF ECONOMIS ANALYSIS FOR ATMOSPHERIC DYE BECKS

(Dye Fluid Only)

29 Dye Beck System

System	Capital Costs	Cost of Yearly Amortization	Annual Replacement Costs	Annual Operating Costs	Annual Water a) Savings	Annual Energy b) Savings	Net Annual (Cost) Savings
ZrO-PAA	$1.4x10^6$	$321,100	$42,000	$11,000	$7,125	$96,250	$(270,725)

System	Capital Costs	Cost of Yearly Amortization	Annual Replacement Costs	Annual Operating Costs	Annual Water a) Savings	Annual Energy b) Savings	Net Annual (Cost) Savings
Zro-PAA	$285,000	$65,366	$8,550	$11,000	$7,125	$96,250	$18,458

a) Savings @ 25¢/kgal
b) Basis compared to 65 F cold water

of the evaluations for the preparation range, dye range, and atmospheric dye becks respectively. For each case the capital cost, yearly amortization cost, annual replacement costs, annual operating cost, water savings, energy savings, and net cost or savings are evaluated.

Some of the situations evaluated are winners and others are losers. The water washer application on the preparation range appears to be unattractive, but if size recovery is practical this situation would be faced with a possible credit of possibly $500,000 for reclaimed size. It is well known that J. P. Stevens Corporation has pioneered in this activity with Union Carbide technology.

The chemical desize washer carries such a heavy loading that permeation is very slow causing relatively expensive water recovery. No chemical recovery is probable and the application has little merit.

The caustic washer appears to be an attractive investment for the recovery of hot water. In addition, the possibility of caustic recovery and reduction in waste aklalinity are attractive growth benefits which will accompany recycles.

The dye range washer water is not hot enough to justify membranes for water reclamation alone. Only if the reuse of acetate as described in the process modification section of this report can be demonstrated and proves valuable will there be an economically based acceptance of such a unit.

Contrary to the dye washer, the soaper washer on the dye range is predicted to be an economically viable installation for all membranes evaluated. All membranes cost a similar amount and have similar benefits on this particularly "easy" feed stream. The spiral (Abcor) membrane lifetime and associated replacement costs appear to be the most significant cost factor different between the installations. As has been mentioned previously, laboratory testing showed that the ZrO-PAA membrane concentrated effective wetting agent toward possible recovery of this material.

The application to a 29 beck (7 foot size) plant of 83 GPM is economically attractive only if the optimistic level of the flux indicated by testing is achieved. The optimistic flux is about 5 times as large as the observed long term value resulting in a capital installation 20% as large. The optimistic flux will only be achieved if the substance responsible for the flux decline be identified and an appropriate remedy be found. In this program the substance was not identified.

7.4 Economic Impact on Industry

In a study conducted for (ERDA)DOE, General Electric [5] determined the number of units and energy consumption of classes of textile finishing equipment. Table 29 is extracted from that source, showing the number of units and respective fraction of energy use of each type unit. Used as a guide, this information indicates the equipment studied herein directly represents 48 percent of the wet finishing processes on an energy basis.

TABLE 29. ENERGY AND NUMBER OF SELECTED PROCESSES

Process	Number	Annual Energy	Consumption
Open-width Preparation	408	1.48×10^{16} J/yr	(1.4×10^{13} Btu/yr)
Rope Preparation	389	1.37×10^{16} J/yr	(1.3×10^{13} Btu/yr)
Thermosol Dye Ranges	132	0.26×10^{16} J/yr	(0.25×10^{13} Btu/yr)
Atmospheric Becks	3918	1.16×10^{16} J/yr	(1.1×10^{13} Btu/yr)
Pressure Becks	740	0.32×10^{16} J/yr	(0.3×10^{13} Btu/yr)
TOTAL		4.59×10^{16} J/yr	(4.35×10^{13} Btu/yr)
STUDY TOTAL-ALL FINISHING		9.63×10^{16} J/yr	(9.1×10^{13} Btu/yr)

From General Electric Survey, approximately 1972 information (Reference 5).

Table 30 shows the impact if membrane recycle were adopted for the five processes studied herein. A 21% water reduction and a 27% energy reduction is expected. The capital required would be something over ¼ billion dollars, and net operating return of about 60 million dollars annually would be achieved. The demand for electric power would increase by about 120 Mw (one eighth of a modern power plant typical installation). All these factors are considered to be reasonably positive in nature as regards to the possibility and gross economic feasibility of membrane installation.

TABLE 30. IMPACT ON INDUSTRY OF FULL MEMBRANE IMPLEMENTATION

Process	Units	Water Reduction (Annual)	Energy Use Reduction (Annual)
Open-Width Preparation	408	$54.4 \times 10^6 m^3$ (14.4×10^6 Kgal)	1.06×10^{16} J (10×10^{12} Btu)
Rope Preparation	389	$51.8 \times 10^6 m^3$ (13.7×10^6 Kgal)	1.02×10^{16} J (9.7×12^{12} Btu)
Dye Range	132	$18.5 \times 10^6 m^3$ (4.9×10^6 Kgal)	0.26×10^{16} J (2.5×10^{12} Btu)
Becks	4658	$35.2 \times 10^6 m^3$ (9.3×10^6 Kgal)	0.54×10^{16} J (5.1×10^{12} Btu)
TOTAL		$1.6 \times 10^8 m^3$ (42.3×10^6 Kgal)	2.88×10^{16} J (27.3×10^{12}Btu)

OR

38% of industry total or 30% of industry total

$112. \times 10^9$ gal* ($4.24 \times 10^8 m^3$)

*SIC 22 total, 1972 Census of Manufacturers

8.0 FULL SCALE PROCESS MODIFICATIONS

Two full scale process modifications related to membrane applications have been evaluated. Both of these have been introduced in the earlier section on possible process modifications. The first, for atmospheric dye application, is critical to the effective recovery of energy by membranes. The second offers a definite economic benefit by itself and a substantial benefit in reducing the cost of a hypothetical membrane unit. In most situations involving textile washers there are two independent parameters-water temperature and flow rate. The flow of water causes the washed off substances to be carried away from the cloth by dilution and mixing. Temperature affects solubilities, diffusion, and viscosity each tending to affect the rate of solute exchange from the cloth to the water. Conceivably the adequate removal of material from the cloth may be achieved at many combinations of temperature and flow. The experiment reported moved from a condition of relatively high flow, low temperature to a condition of lower flow, higher temperature. In both conditions, the cloth was adequately prepared in that the plant's stringent quality measures were satisfied.

8.1 High Temperature Dye Addition Experiment

The purpose of the trial dyeing was to evaluate the influence of using simulated recycle hot water on a dyeing process conducted at 82 C. All of the dyeing steps were conducted at 82 C with dyes and salts added separated, each over a one-hour period to determine the feasibility of reuse of hot water in the dye cycle. The following procedure was used for the dye cycle:

(1) Water was introduced into the beck to the desired level.
(2) The cloth was then added to the beck.
(3) Wetting and buffering agents were then added to the beck.
(4) The temperature was then raised to 82 C.
(5) After the temperature of 82 C was reached, the dye solution was added slowly over a one-hour period. The beck solution behind the baffle was manually stirred as the dye was introduced into the beck.
(6) At the completion of the dye addition, the cloth was allowed to dye for twenty minutes before the salt was added.
(7) Salt (NaCl, saturated) was added to the dye bath over a one-hour period at 82 C with stirring to give a slow and even application of the salt solutions.
(8) After the addition of the salt was complete, the bath was cooled to 60 C.

Dye Formula 501
Lot 647
41 yards
Pattern 112-0
Color 133
Wt/Yd 1.31
Weight 53.71
Pieces 1
Level 7

Dye/Chemical Name	Amount
Amaterge T	1.0750 pounds
Direct Dyes	0.0714 pounds
Fix GD	1.0750 pounds
Salt, Liquid	3.5000 pounds

The foregoing procedure produced a dyeing in a critical shade which met normal quality standards. This test dyeing followed an unsuccessful prior attempt in which the dye and chemicals were added about three times as fast and the stirring behind the baffle was not done. In the earlier attempt some variations in color were produced. The demonstration is not absolutely convincing but does indicate the feasibility of this critical process.

8.2 Open-width Preparation Range

Following the energy survey of the open-width preparation range two actions were implemented by the plant. Flow meters were purchased to document the actual flow. A flow-temperature modification at full scale under standard processing quality requirements was performed. Also, water exiting from the peroxide washers was counterflowed to the caustic washer. It was inserted in the third of the four washers (counting in cloth direction). The plant was able to maintain the required high quality after the flow change even with less chemical additions.

The motivation for manipulating the flow variables on the range is (1) to conserve water and possibly energy by operating at lower flow and higher temperature and (2) by reducing the water flow to enable the most economical hyperfiltration installation. Generally membranes are more productive at high temperature and a smaller system will be required for less flow capacity.

The previous and modified conditions on the range are shown in Table 31. The modified flows are considerably lower than the actual previous rates and are allowed by increasing the temperature. The last column reflects the change in energy flow to drain at each section. Only the water desize wash requires more energy at the new condition while the others require much less. Because the cloth exposed to atmosphere is hotter, a greate evaporation rate calculated by the same procedure as for Table 2 is anticipated as indicated by Table 31. However, the net change favors operation at higher temperature. Also the water borne energy was previously 76% of the total while after the change only 52% of the energy is exhausted with the hot water. The reason for this is that the energy to drain has been diminished and the other energy requirements have been increased.

TABLE 31. FLOW AND TEMPERATURE MODIFICATIONS

	Previous Flow @ T (dm^3/s @ °C)	Modified flow @ T (dm^3/s @ °C)	Change in $\dot{E}$ GJ/hr
Water Desize Wash	4.41 @ 60	2.59 @ 93	+0.202
Chemical Desize Wash	3.15 @ 82	1.39 @ 88	-1.571
Caustic Wash	4.41 @ 82	1.58 @ 91	-2.51
Bleach Wash	3.15 @ 76	1.58 @ 93	-0.97

Estimated increase in vapor loss = + 3.32 GJ/hr
estimated net energy change = - 1.53 GJ/hr
Previous total use 16.9 GJ/hr (reference)
Energy reduction 9%
Flow reduction 47%

APPENDIX A

FUNDAMENTAL EVALUATION OF EVAPORATIVE AND CONVECTIVE HEAT LOSS IN FULL-SCALE TEXTILE EQUIPMENT

The magnitude of heat loss by convection and evaporative mechanisms in typical textile equipment is not documented in the literature so it was decided to perform some basic field experiments to determine the magnitude of such losses. Because of the nature of the experiments and the instruments used it is difficult to assert any high accuracy estimate; however, the data are felt to be useful to estimate the amount of energy loss by the combined mechanisms. One similar experiment was run during the course of our work, the data from which are supplied herein for comparison.

The first experiment was conducted on dye becks from 3 to 12 feet in width shown in schematic cross-section in Figure A1. During normal dyeing procedures the beck temperature decline on cooling was recorded. The simple equation which follows was used to calculate heat loss rate.

$$Q = -mc\, dT/dt$$

Q is the heat loss rate by all mechanisms
m is the mass of water, cloth, and affected beck portions
c is the specific heat of mass m
dT/dt is the temperature derivative with respect to time or the change in temperature with time.
Generally, the losses external to the beck are very small, much smaller than the error inherent in the procedure, and were summarily neglected.

Procedurally, the time derivative is difficult to calculate accurately. We used three methods to estimate its effect, each of which has weaknesses.
Method A) Fit an exponential curve to the data.
Method B) Fair a curve through the plotted data and extract tangents at various points.
Method C) Use straight line segments between successive data.
Having tried all the above and comparing the results we have proceded to interpret the data as described in the following.

The data were examined for effect of beck width and no systematic effect was found. Therefore all data were normalized by the beck width. It is considered intuitively satisfying that width should offer no variation, since both the cloth surface and water surface do not vary

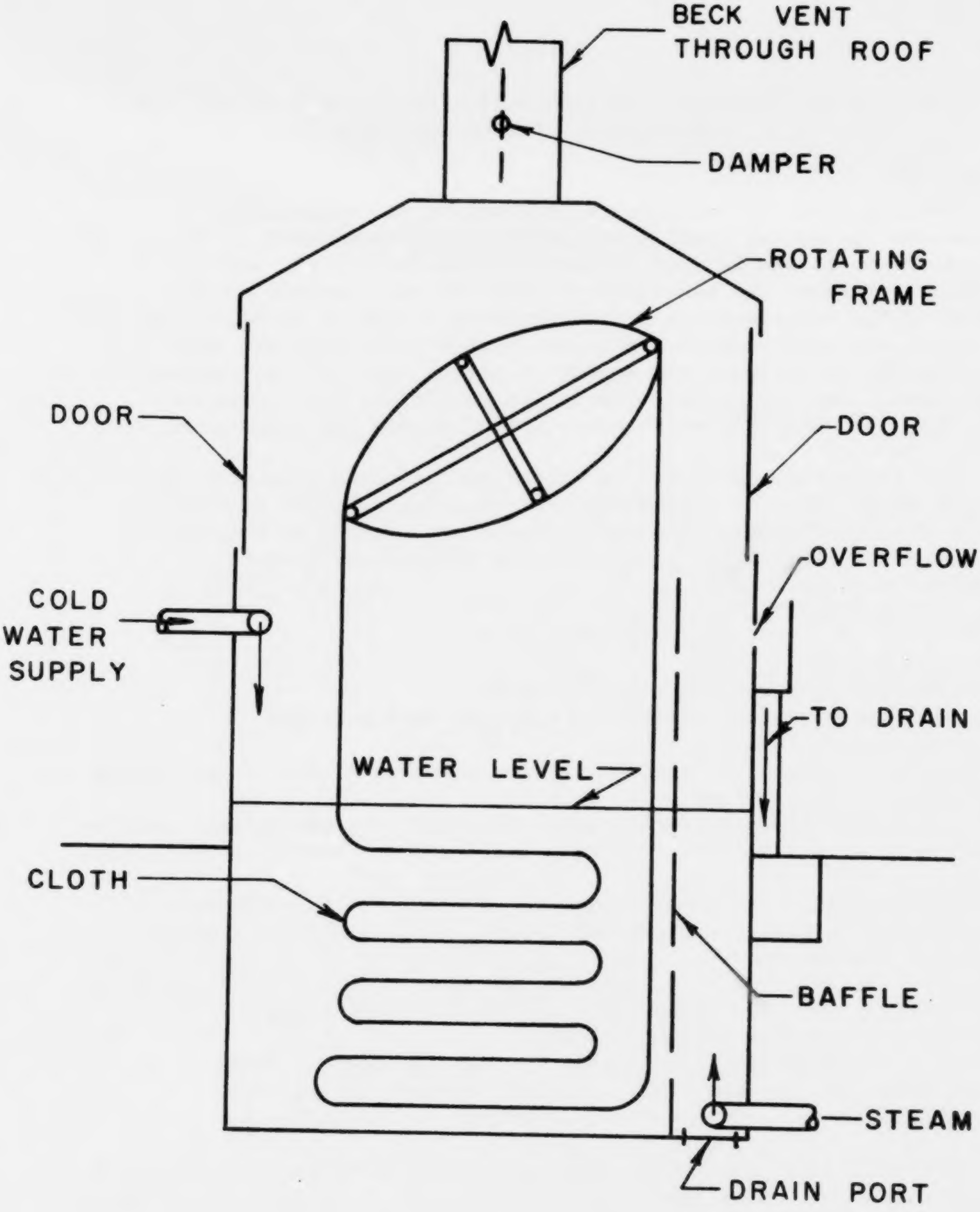

BECK VENT THROUGH ROOF
DAMPER
ROTATING FRAME
DOOR
DOOR
OVERFLOW
COLD WATER SUPPLY
TO DRAIN
WATER LEVEL
CLOTH
BAFFLE
STEAM
DRAIN PORT

FIGURE A1 SCHEMATIC DIAGRAM OF AN ATMOSPHERIC BECK

with beck width normally. Theoretically the evaporation rate will vary in proportion to the vapor pressure at the liquid surface temperature since the vapor pressure in the incoming air is small. Upon dividing the heat loss rate per width of beck by the vapor pressure at the observed beck temperature, the data are as presented in Figure A2. There is a tendency for the magnitude of this "mass transfer coefficient" to decrease somewhat as the temperature increases. The decrease may be due to any one of several factors and considering the experimental uncertainty may not actually exist. The data from Reference 6 are seen to agree with those observed.

The above data were observed under the conditions with the vent damper open and the door to the beck closed. Opening of the door (with damper open) causes an estimated 20% increase in less rate. The closing of the damper may result in a 50% decrease in loss rate below that presented. Our data with damper closed are much fewer than with damper open and the exact decrease in values so crudely determined is difficult to assert with confidence. That there is a change is undoubted, however. Figure A3 shows the observed variation of temperature in time for three runs. In one, the damper was open and the door closed from the highest temperature. In another the damper was open and the door open and the door closed at about 86 C, at which time a noticeable decrease in temperature decay occurred. Finally a third run with door and damper closed was changed to both open and a more rapid drop ensued. These data show conclusively that the positions have a strong effect.

The second experiment was conducted in a wash box on a continuous range depicted schematically in Figure A4. Cloth carrying water from a similar box at 89 C enters the box and flows in a serpentine fashion through the wash water. Water is added to the box and direct steam injection provides heat to control the temperature. Two experiments were run. In one, the water supply temperature was adjusted to exactly equal the outflowing water temperature and the steam was shut off. Equilibrium was reached at 63 C at which condition the difference in energy content of the cloth and water at 89 C entering and 63 C existing supplies the losses from the cloth. This energy loss rate is assumed to correspond with the 63 C level although a considerable portion is lost from the cloth in transit between the upper and subject box. In the second experiment the water supply was shut off and temperature raised by steam addition. When the steam was terminated, a record of temperature decline was made. The heat loss is then calculated from

$$Q = -Mc\ dT/dt + (\dot{m}_1 c_1 + m_2 c_2)(89 - T)$$

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[6] Woodall, L. C. and E. F. Godshall, "Energy Economics in a Dyehouse," presented at Clemson University, Energy Conservation in Textile Industry, January 12-13, 1977.

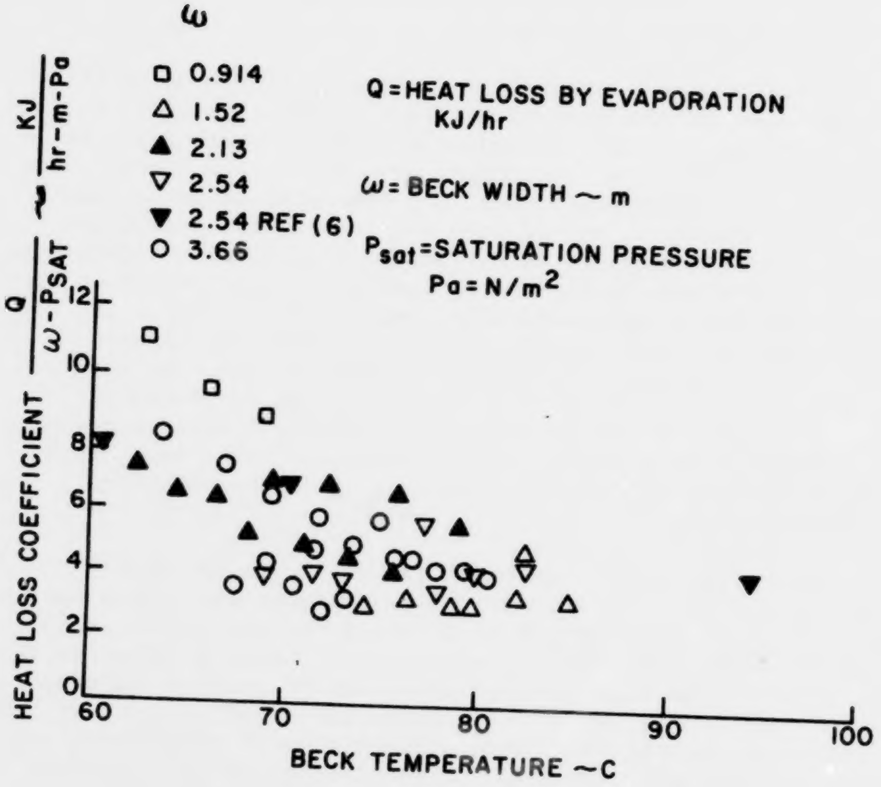

FIGURE A2 CORRELATION OF EVAPORATIVE LOSS DATA FOR ATMOSPHERIC BECKS

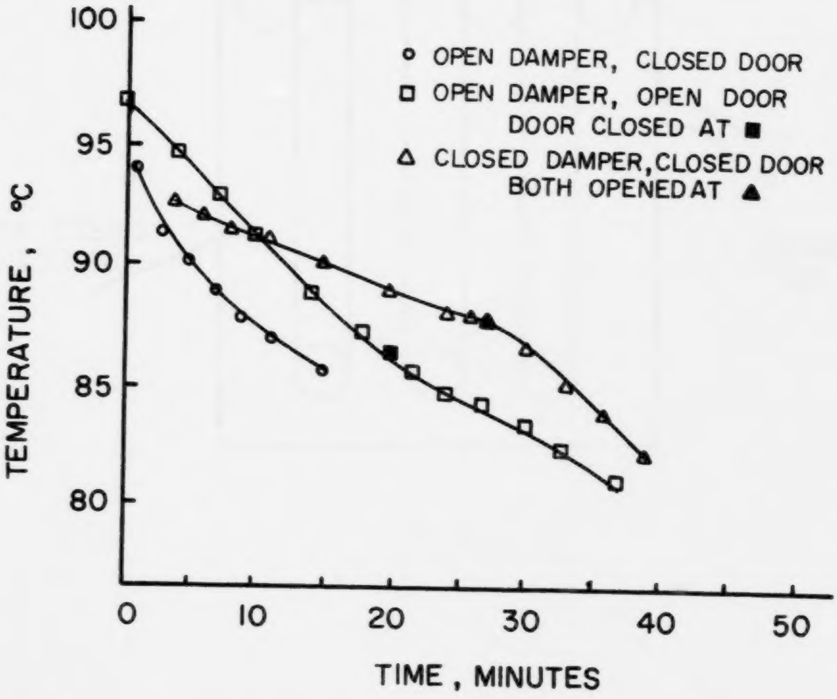

FIGURE A3 TEMPERATURE TRANSIENTS SHOWING EFFECTS ON PORTAL CONDITIONS

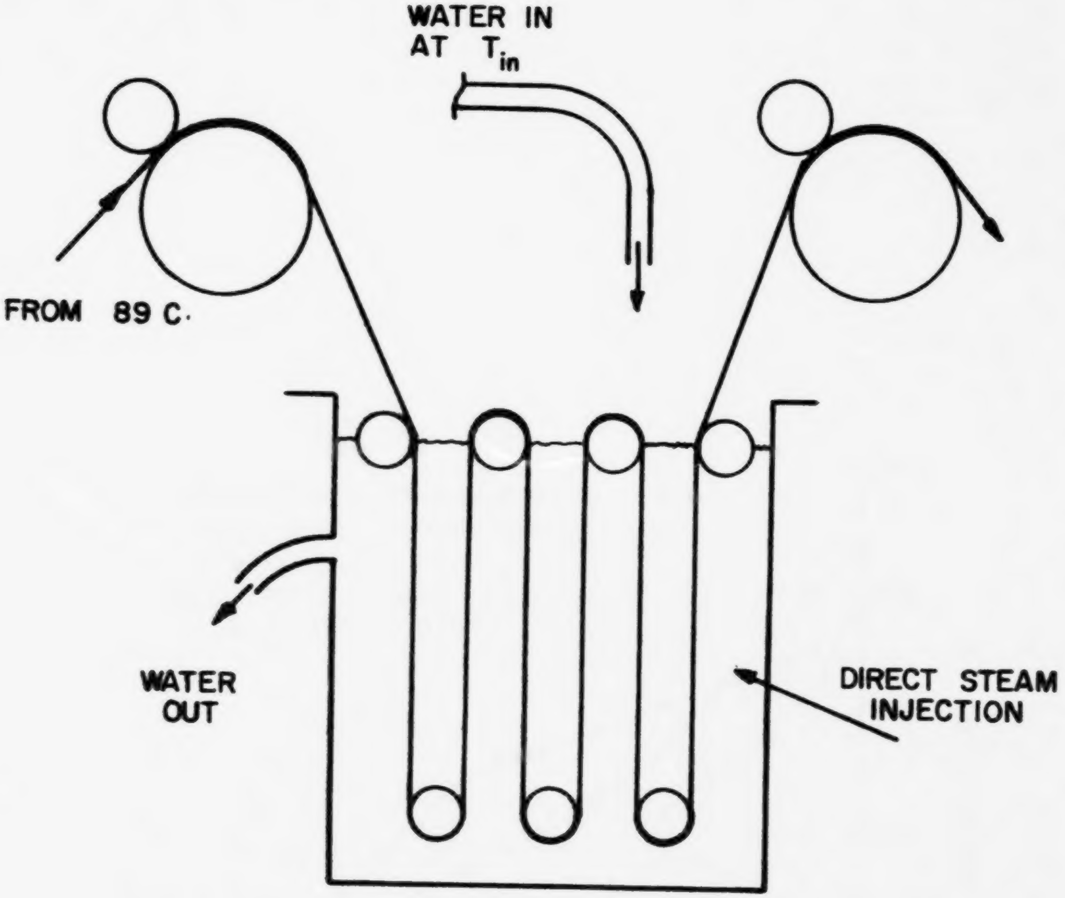
WATER IN
AT T_{in}
FROM 89 C
WATER OUT
DIRECT STEAM INJECTION

FIGURE A4 SCHEMATIC OF WASHER USED FOR HEAT LOSS STUDY

Q is the heat loss at temperature T
Mc the sum of mass and specific heat products for the water, contained cloth, etc.
$\dot{m}_1 c_1$ is the mass flow rate and specific heat of the cloth
$m_2 c_2$ is the mass flow rate and specific heat of the water carried on the cloth
dT/dt is the time rate of change of temperature T
89 is the upstream source temperature.
The results of these experiments are shown in Figure A5. The loss rate very nearly coincides with the vapor saturation pressure curve as indicated by the correlating equation fit to the data obtained.

For estimation purposes, the area of liquid and cloth (one side) have been used to normalize both the data for the wash box and the beck. This calculation results in a single equation

$$Q = 2 \times 10^{-4} A P_{sat}$$

Q is the loss rate in kJ/s (kW)
A is the area of liquid and one side of the cloth involved in m^2
P_{sat} is the vapor pressure at a given temperature in N/m^2 (Pa).
The equation agrees with both the beck and wash box experiences and has been used to estimate losses occurring from wet cloth surfaces in rope form, approximate division of losses within components, and the impact of modifications. Use of the equation in situations having significant inhibitions of air circulation is considered imprudent.

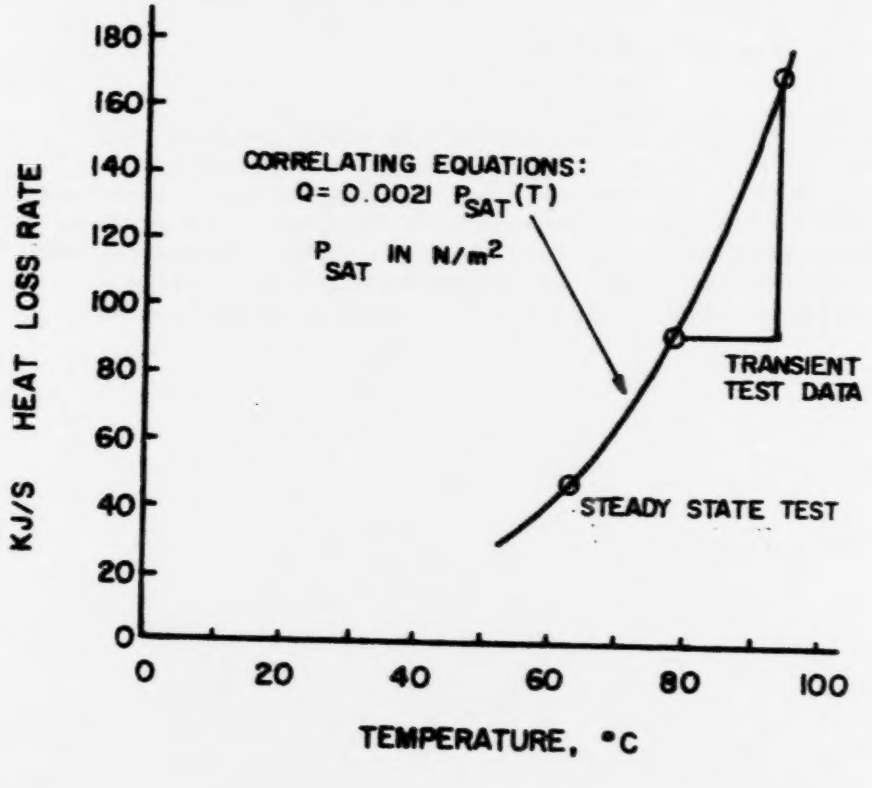

FIGURE A5 VARIATION IN OBSERVED HEAT LOSS WITH TEMPERATURE

APPENDIX B

CALCULATION OF EXTERNAL RADIATIVE AND CONVECTIVE HEAT LOSSES IN TEXTILE EQUIPMENT

Heat loss by convection and radiation external to equipment has been calculated using models and procedures in common use. Radiation from an object at T_1 to its surroundings at T_2 obeys a relation of the form

$$q = \sigma F_e F_a (T_1^4 - T_2^4)$$

q is the heat flow per unit area
σ is the Stefan Botlzmann constant 5.67×10^{-8} ($Wm^{-2}K^{-4}$)
F_e is a factor used to account for the radiation emission properties of the involved surfaces
F_a is a view factor (fraction of total view of 1 occupied by 2).

For simplicity F_e and F_a are assumed to be unity. The assumption may be poor for F_e if the material is a bare metal in which case the calculation will over-estimate the actual loss. Under such an assumption the above equation may be factored and arranged as

$$q = h_r \ (T_1 - T_2)$$

$$h_r = \sigma (T_1 + T_1)(T_1^2 + T_2^2)$$

For values of T_1 and T_2 the range 300-350K, h_r is well approximated at 5.7 W/m^2 C (1 Btu/hr-ft^2-F) and this value is adopted.

In free convection in air from vertical plates, horizontal cylinders, or horizontal plates[1] gives equations from correlations of data as

$$h = (0.95 + 1.43)(T_1 - T_2)^{1/3} \ W/m^2\text{-}K$$

$$q = h(T_1 - T_2)$$

In the range up to $T_1 - T_2 = 50$ C, values of h are approximately in the range of 5 W/m^2-K. Values for forced convection are by comparison expected to be small except perhaps in cases of high localized heat transfers accompanying high inpinging air velocities.

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[7] J. L. Holman, Heat Transfer, McGraw-Hill, 1976 (4th Edition).

Our calculations are based in the assumption of a total radiation plus convection loss described by

$$q = h(T_1 - T_2)$$

$$h = 11.34 \text{ W/m}^2\text{-K } (2 \text{ Btu/hr-ft}^2\text{-F})$$

Inasmuch as the losses calculated are expected to be above the actual amount and the calculated losses are generally quite small in comparison with evaporative losses, this procedure is deemed sufficient.

APPENDIX C

ENERGY USE IN ATMOSPHERIC BECK PROCESSES

DESCRIPTION OF FACILITY AND DYEING PROCESS

Dye House Facility

The facility observed employed five different sizes of atmospheric becks ranging in capacity from approximately 1000 to 2200 gallons in the dyehouse. At the same that this work was begun, there were 32 operating dye becks in the dyehouse, 10% of which would be undergoing maintenance at any one time. The becks are essentially manually operated, though temperature recorder-controller units regulate the rate of temperature rise during the heating-up events and maintain the temperature at a nearly constant value during elevated temperature operation. The becks are installed so that the access doors are at a convenient height with respect to the operation floor level; that is, the becks are in a pit which dips to about four feet below the operating floor level (see Figure C1). In order to avoid severe burns to the operating personnel, the becks were vented, and fans circulate air through the becks and out through the building roof. The design is such that air circulates through a given beck only when the beck door is open.

Dyeing Process

Dyeing in an atmospheric beck is done as a batch process with both natural and synthetic fibers being dyed in lots from 50 yards (∿60 lbs) to 1600 yards (∿2000 lbs). The becks are supplied with steam, water, and chemicals at the proper times during the dye cycle to accomplish the scouring, dyeing, and dye fixing for the cloth. A large amount of cloth is loaded into a beck so that almost all of the cloth is immersed in the water. Several endless loops of cloth are used, with a small amount of cloth in each loop passing over the rotating frame (see Figure C1). This rotating frame causes the loops of cloth to be continuously circulated through the chemical solutions during a dye cycle. Circulating the cloth in this manner serves two purposes: First, it causes the cloth to be uniformly exposed to the process chemicals; and second, it keeps the solution stirred for more even distribution of chemicals and temperature within the bath.

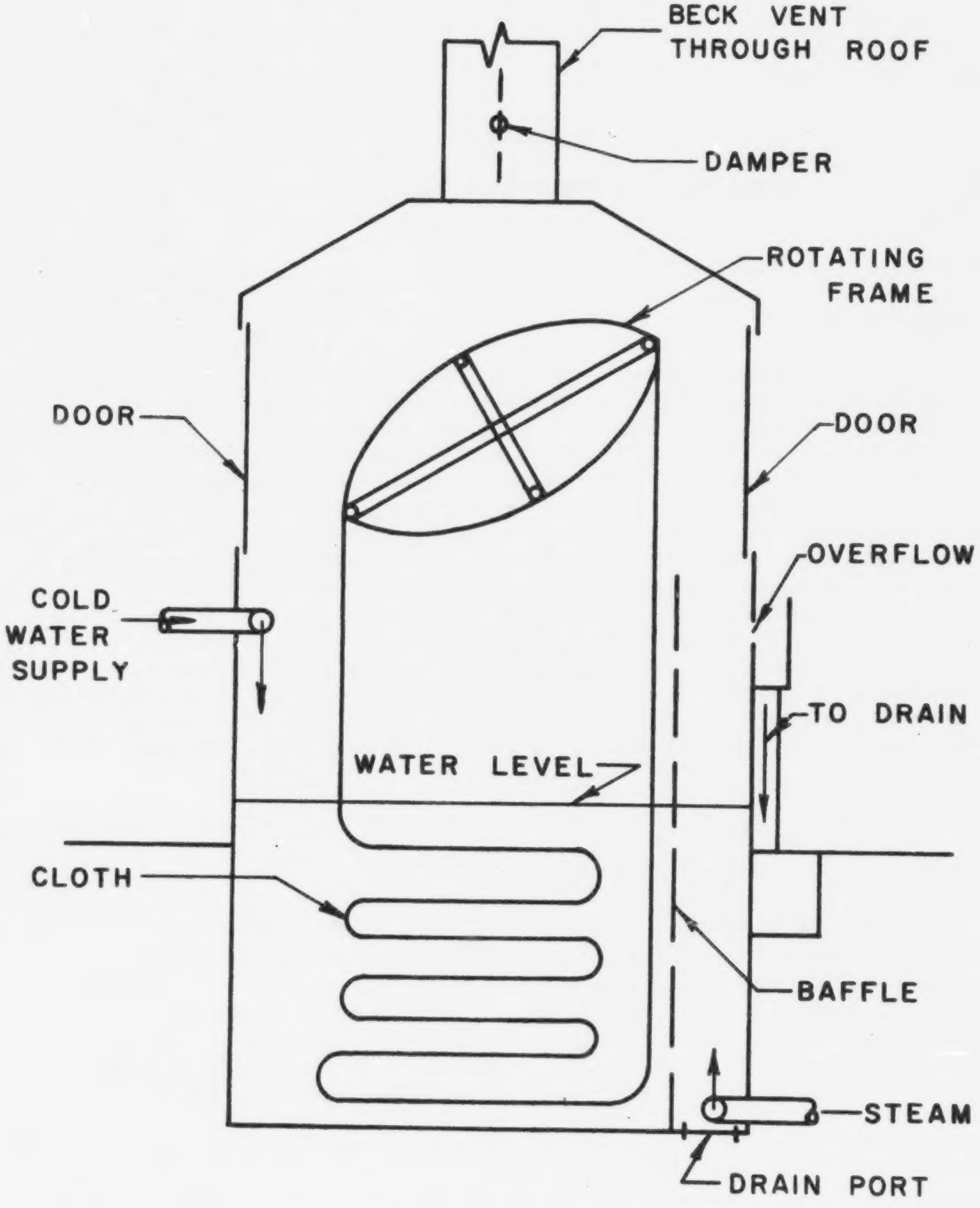

BECK VENT
THROUGH ROOF
DAMPER
ROTATING
FRAME
DOOR
DOOR
OVERFLOW
COLD
WATER
SUPPLY
TO DRAIN
WATER LEVEL
CLOTH
BAFFLE
STEAM
DRAIN PORT

FIGURE C1 SCHEMATIC DIAGRAM OF AN ATMOSPHERIC BECK

The normal dye cycle has three distinct phases: first, the cloth is scoured (cleaned and bleached); second, the dyeing is accomplished by exposing the cloth to a high-temperature dye bath for a relatively long period of time; and third, the cloth is exposed to chemicals which "fix" the dye so that the colors are fade resistant and so that the dye does not migrate in the wet cloth during the remaining processing within the plant. Correspondingly, there are three times when hot liquid is discharged from the dye beck into the plant waste stream. These discharges are accomplished by adding cold water to the beck (see Figure C1) so that the liquid rises and overflows into the sewer. The cold water rinse both cools the beck contents and flushes the processing chemicals out of the cloth. Normally, a beck is completely drained only after flushing for a long enough time for the water to become clear. Two typical cooling rates are shown in Figure C2. For the first 17 minutes (approximately) a low cooling water flow rate assured that the cloth cooled slowly enough to avoid wrinkles; the cooling water flow rate was then increased to finish the cooling and washing process. From the curves of Figure C2 cooling water flow rates of 34 gal/min and 225 gal/min were calculated for the two stages of this process. For those fabrics which do not wrinkle easily when cooled rapidly, the cooling water is admitted to the beck for the whole process at the higher rate of 225 gal/min. In either case, the total amount of water required is the same if the same final temperature is reached. In the cases illustrated in Figure C2 the becks were drained after their contents were cooled to about 100°F.

Plots of temperature versus time for typical complete dye cycles are shown in Figures C3 and C4. Figure C3 is for a cycle which includes the scour, dye and dye fix phases, while Figure C4 is for a cycle having only the dye and dye fix phases. The scour phase was used only for automotive fabrics, which constitute about one-third of the batches of cloth dyed. The various events of the cycle are indicated in Figures C3 and C4, and are listed here:

(1) Cold water (at the average daily atmospheric temperature is admitted to the dye beck and is heated to between 90°F and 120°F.
(2) The cloth is loaded into the beck.
(3) Scouring (cleaning) chemicals are added to the water, and, while the cloth is circulating through this solution, the temperature is increased to, and maintained at, 160°F for about one-half hour.
(4) The scouring chemicals are flushed out of the beck and rinsed from the cloth. (This requires a large amount of "cold" water.)
(5) Fresh water again fills the beck and is heated to between 90°F and 120°F.
(6) The dye chemicals are added to the water.
(7) The solution is heated and maintained at about 190°F for sufficient time to color the cloth to the desired shade.

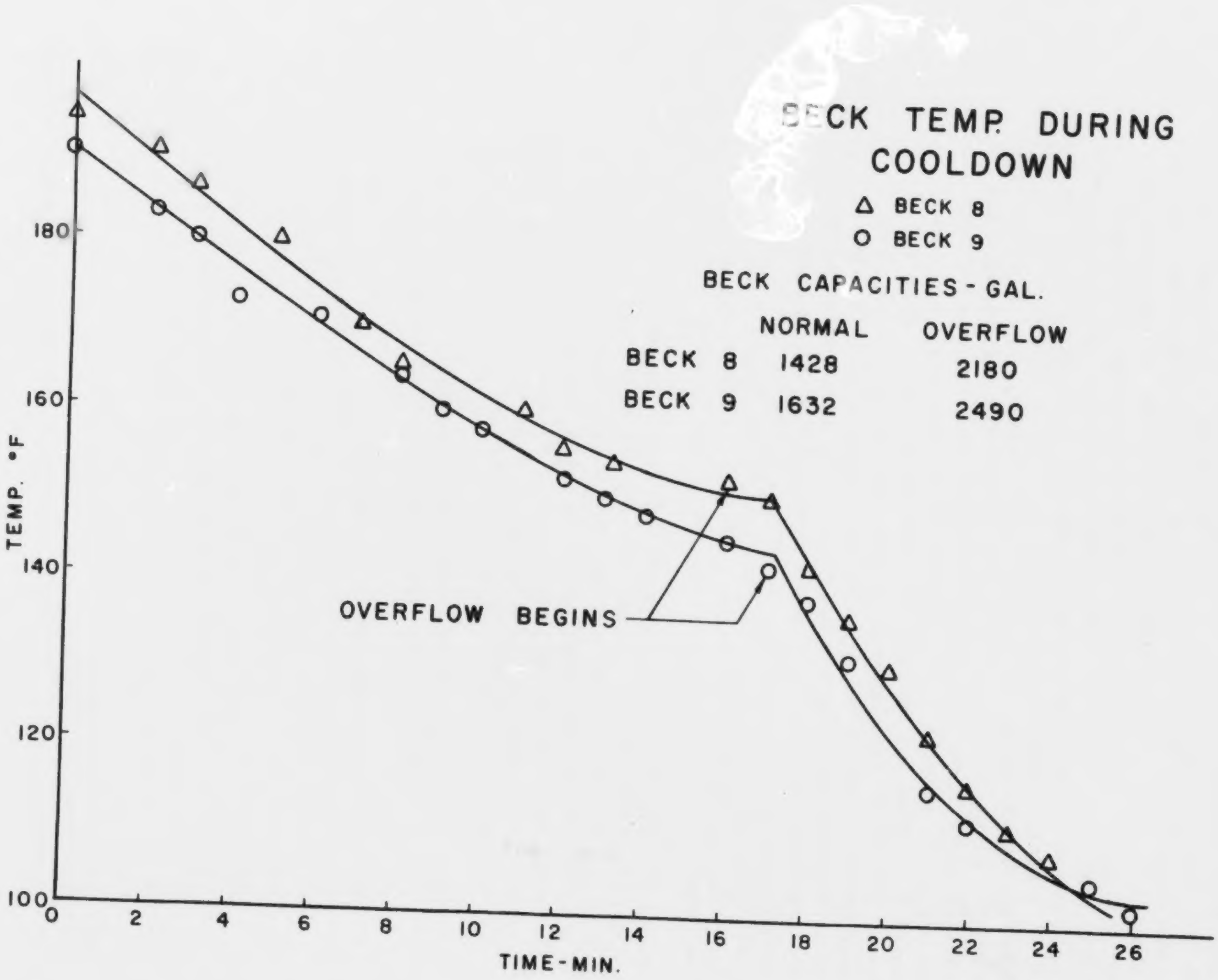


FIGURE C2 TYPICAL BECK COOLING CURVES

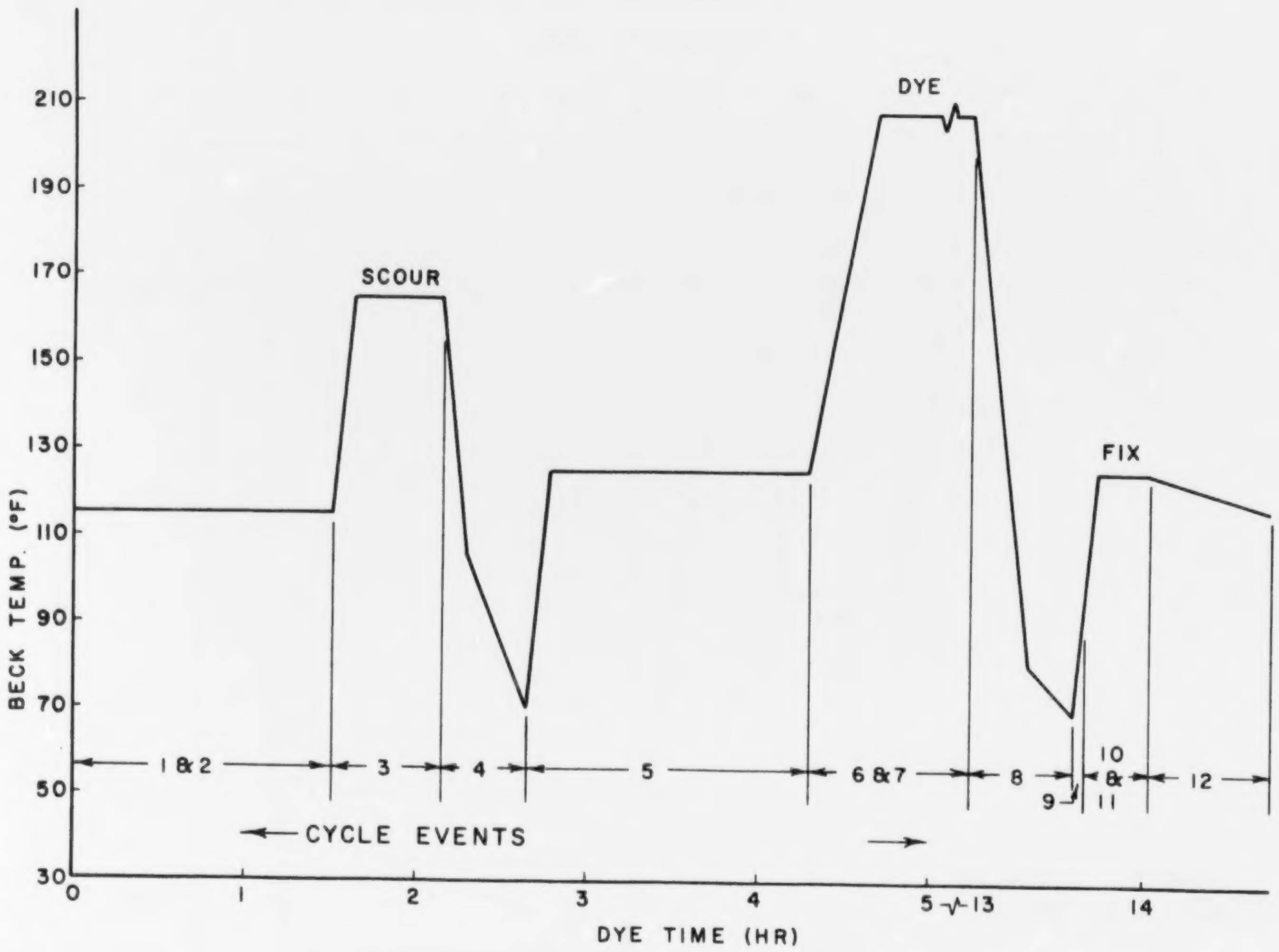


FIGURE C3 TEMPERATURE CYCLE FOR ATMOSPHERIC BECK WITH SCOUR

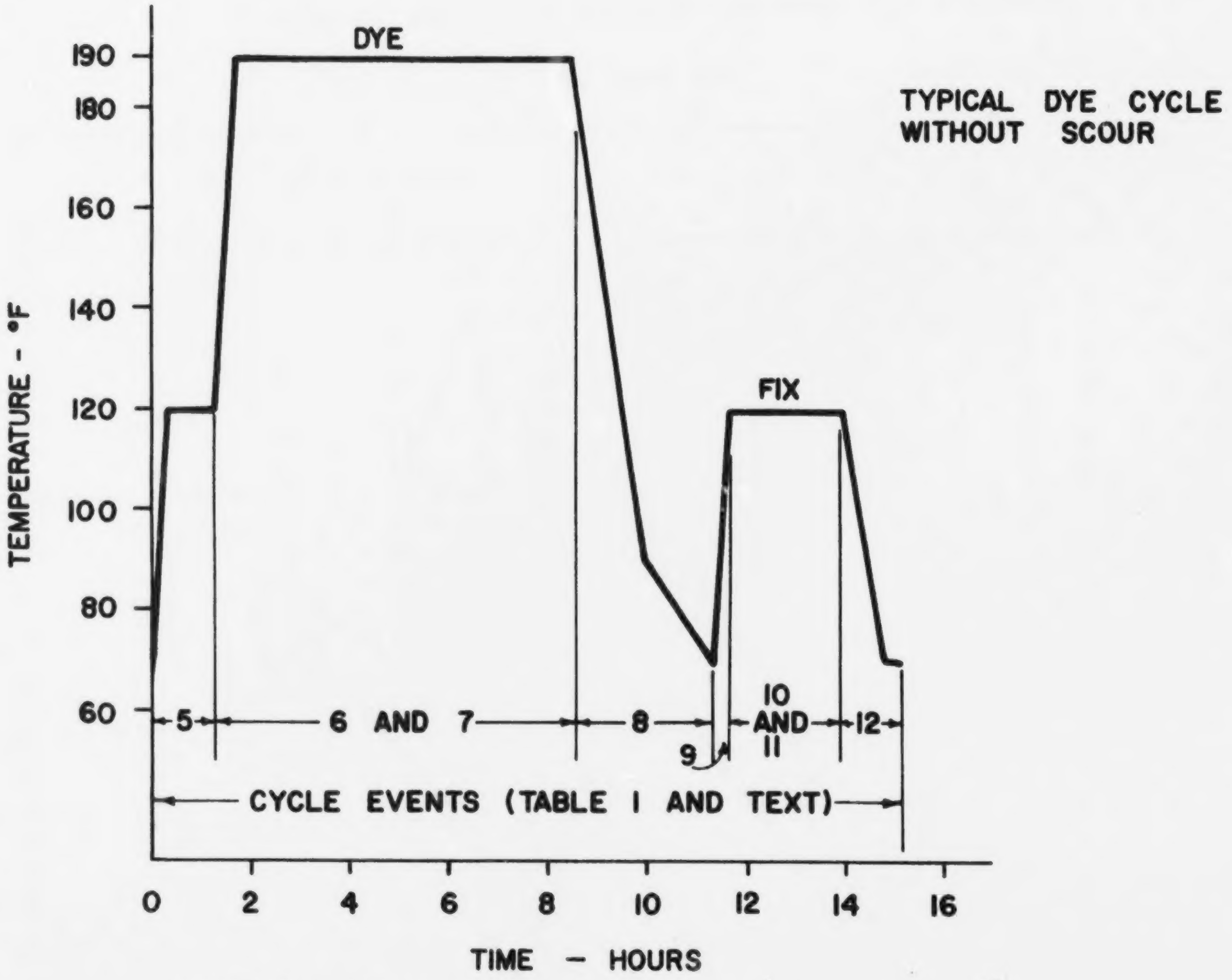


FIGURE C4 TEMPERATURE CYCLE FOR ATMOSPHERIC BECK WITHOUT SCOUR

Sometimes it is necessary to add more dye during this event. These "adds" are made at operating temperature.

(8) The dye solution is flushed out of the beck and rinsed from the cloth. (This, again, requires much cold water.)

(9) Cold water is admitted to the beck again and is heated to between 90°F and 120°F.

(10) Chemicals used to make the dye "color fast" are added to the water.

(11) This solution is heated to about 120°F and maintained at that temperature for about 15 minutes.

(12) These dye "fixing" chemicals are flushed from the beck and carefully rinsed from the cloth. (Again, much cold water is used.)

(13) The cloth is unloaded from the beck and sent to the dryer.

ANALYSIS OF ENERGY AND WATER CONSUMPTION IN THE DYEHOUSE

A detailed study of the energy and water usage in the dyehouse was undertaken to determine the potential for reclamation. During the course of this study two different methods were used to calculate the energy and water consumption per pound of cloth processed. In the first method an energy and water mass balance is made on the dyehouse without reference to the individual dyeing cycles. The dyehouse is taken as a black box, and the total water and energy use is calculated from the inlet and discharge water flow rates and temperatures, and the steam consumption in the dyehouse. The second methods is based on the analysis of selected dye cycles to determine the energy and water consumted per pound of cloth processed during that cycle. Three cycles, two representing the average cycle (with and without scour) and the other a typical cycle (with scour), were studied in detail for this purpose.

The following outline will be adhered to in the analysis. First the two methods will be discussed in detail with specific references to the data used. Then the results will be compared and discussed. Finally, losses from the becks during the dye cycle will be examined, and suggestions will be made that may cut down the losses and reduce operational expense.

Method I

The first method utilizes the lump analysis techniques. An energy balance is made on the dye as shown in Figure C5.

STEAM
COLD WATER
COLD AIR

DYEHOUSE

CONVECTION AND RADIATION
WARM WATER
WARM, MOIST AIR

Figure C5. Schematic Energy Diagram.

$$Q_{steam} + Q_{water\ in} = Q_{losses} + Q_{water\ out}.$$

Thus knowing the inlet (filter plant) and discharge (composite waste) water temperatures and flow rates and the steam consumption, we can determine the total energy loss from the dyehouse. Furthermore, from heat transfer considerations the convection and radiation losses can be evaluated independently, making possible the determination of evaporation losses from the becks (an essential point in evaluating beck performance). The relative magnitude of the losses can be studied to determine if energy-savings measures that might involve capital expenditure can be justified. The energy content of the composite waste can then be examined to evaluate the potential for energy reclamation. The results of the calculations are given in Table C1.

TABLE C1. TOTAL ENERGY QUANTITIES FOR THE MONTH OF MAY, 1975 (10^6 Btu)

	Losses		
Q_{steam}[a]	$\Delta Q_{water\ out}$[b]	$Q_{evaporation}$	$Q_{radiation\ \&\ covection}$
10428	4136	6116	176

[a] Assuming 75% boiler efficiency and that 90% of the steam production is used in the dyehouse.

[b] Energy potentially available for reclamation is 4136 10^6 Btu.

The measured data include water inlet temperature, water discharge temperature, and the water flow rate as determined by adjusting the filter plant output to the amount that goes to the dyehouse. The average temperature rise of the water in passing through the dyehouse was 14.5°F during the three-day test period.[a] The cloth production by the dyehouse during that time was 320,000 yards, which at an average weight of 1.26 lbs/yd was 403,200 pounds of cloth. Taking into account the fact that redyes for this type of production are in the range of 30-40%, the dyehouse processed about 544,000 pounds of material. The plant operated for 22 days in that month, and the dyehouse used 10,428 x 10^6 Btu's of steam and 29.2 x 10^6 gallons of water. Hence the energy and water consumption per pound of cloth processed can be calculated in the following way:

---

[a] This temperature rise can vary from time to time as a result of variations in the color and types of cloth dyed, and because the steam and water valves are controlled by the operating personnel rather than an automatic controller.

Energy used per pound of cloth processed: $\frac{10,428 \times 10^6}{544,000} = 19,170$ Btu/lb

Water used per pound of cloth processed: $\frac{29.2 \times 10^6}{544,000} = 53.7$ gal/lb

Method II

The second method uses a typical (with scour) and two average (with and without scour) cycles[b] to determine energy and water consumption per pound of cloth processed in the dyehouse. As mentioned earlier, two distinct dyeing cycles are used. The dye cycle withour scour corresponds to about two-thirds of the total number of batches of cloth dyed. The cycle with scour, now used only for automotive fabrics, takes up the remaining one-third.

All the available temperature charts from the dyehouse of the week of September 29, 1975, were examined. Averages were obtained of the duration and operating temperature of each of the events during a dye cycle, and with this information the average cycles with and without scour were constructed. The typical cycle was selected arbitrarily and happened to be a cycle with scour. The temperature histories of the event of the average cycles with and without scour and of the typical cycle are given in Tables C2, C3, and C4, respectively.

Using this data the energy and water consumption per pound of cloth processed were calculated for each one of these selected cycles. The results of these calculations are given in detail in Tables C2, C3, and C4 for the typical cycle, and average cycles with and without scour, respectively. Also included in these tables are the energy consumption to heat the contents of the beck from the inlet to the operating temperature, the energy consumption to maintain at operating temperature (to compensate for losses), the total energy consumption, the hourly rate of total energy consumption, energy content of the water in the beck, and the total water usage for each event as well as the cumulative quantities for the cycle itself.

Table C5 compares the energy and water consumption per pound of cloth processed for the selected cycles. Recalling that the overall ratio of cycles without scour to cycles with scour is 2:1; we may better represent the data by defining the "average" cycle as

"average" cycle - 2/3 (average cycle without scour) +
1/3 (average cycle with scour).

---

[b] These cycles were assumed to be run in a 7-foot (width) beck with an operating capacity of 1428 gallons (11,900 pounds) of water.

TABLE C2. TYPICAL DYE CYCLE

Event		1 & 2	3	4	5	6 & 7	8 & 9	10 & 11	12
Duration	min	91.5	37.5	30.00	99.0	552.0	45.0	21.0	42.0
Temperature	°F	115	165	-	125	208	-	125	-
Energy Consumption to heat from 65°F to operating temp ($\rho V C p \Delta T = QH$)	Btu x 10^6	0.594	0.622	-	0.713	1.042	-	0.713	-
Energy Consumption to maintain at operating temp ($\rho V C p \frac{dT}{dt} \Delta T = QM$)	Btu x 10^6	0.192	0.286	-	0.276	11.597	-	0.058	-
Total Energy Consumption ($QH + QM + QT$)	Btu x 10^6	0.786	0.908	-	0.989	12.639	-	0.771	-
Rate of Energy Consumption at T ($QT/\Delta t$)[a]	millons of Btu per hour	0.15	0.86	-	0.21	1.41	-	0.21	-
Energy Content of water in beck about 65°F (including steam condensate)	Btu x 10^6	0.622	1.304	0	0.753	1.944	0	0.753	0
Water Flow Rate Low/High	gal/min	225	-	35/225	225	-	35/225	225	35/225
Water Used	gal	1493 (hot)	72 (hot)	3520 (cold)	1507 (hot)	125 (hot)	6895 (cold)	1507 (hot)	6220 (cold)

Cumulative Energy = 16.093×10^6 Btu
Cumulative Water = 21339 gallons
Cumulative Hot Water = 4748 gallons
Cumulative Cold Water = 16635 gallons

$QH = 3.600 \times 10^6$ Btu
$QM = 12.409 \times 10^6$ Btu
654.5 # of cloth processed

Energy $\frac{16.093 \times 10^6}{654.5}$ = 24460 BTU/# cloth

Water $\frac{21339}{654.5}$ = 32.6 gal/# of cloth

---

[a] To heat at 3°F/min requires ∿2.1×10^6 Btu/hour.

TABLE C3. AVERAGE DYE CYCLE WITH SCOUR

Event		1 & 2	3	4	5	6 & 7	8 & 9	10 & 11	12
Average Duration	min	43.2	85.8	60.0	73.8	437.4	165.0	160.8	68.4
Temperature	°F	115	160	-	115	205	-	120	-
Energy Consumption to heat from 65°F to operating temp ($\rho V C p \Delta T = QH$)	Btu x 10^6	0.595	0.560	-	0.594	1.119	-	0.654	-
Energy Consumption to maintain at operating temp ($\rho V C p \frac{dT}{dt} \Delta t = QM$	Btu x 10^6	0.091	0.251	-	0.155	9.577	-	0.352	-
Total Energy Consumption ($QH + QM = QT$)	Btu x 10^6	0.685	0.811	-	0.749	10.696	-	1.006	-
Rate of Energy Consumption ($QT/\Delta t$)[a]	millions of Btu per hour	0.15	0.55	-	0.15	1.4	-	0.20	-
Water Flow Rate Low/High	gal/min	225	-	35/225	225	-	35/225	225	35/225
Water Used	gal	1428 (hot)	146 (hot)	7345 (cold)	1493 (hot)	1627 (hot)	7345 (cold)	1512 (hot)	7345 (cold)

Cumulative Energy = 13.947 x 10^6 Btu
Cumulative Water - 26720 gallons
Cumulative Hot Water = 4729 gallons
Cumulative Cold Water = 22035 gallons
$QH = 3.477 \times 10^6$ Btu
$QM = 10.426 \times 10^6$ Btu
For a week 109,936 # of cloth processed (183 lots)
600.74 #/lot

Energy $\frac{13947 \times 10^6}{600.74} = 23,200$ Btu/# of cloth

Water $\frac{26770}{600.74}$ - 44.5 gallons/# of cloth

[a] To heat at 3°F/min requires ∿2.1 x 10^6 Btu/hour.

TABLE C4. AVERAGE DYE CYCLE WITHOUT SCOUR

Event Average		1 & 2	3	4	5	6 & 7	8 & 9	10 & 11	12
Duration	min	-	-	-	73.8	437.4	165.0	160.8	68.4
Temperature	°F				115	190	-	120	-
Energy Consumption to heat from 65°F to operating temp ($\rho V C_p \Delta T = Q_H$)	Btu x 10^6	-	-	-	0.594	0.933	-	0.654	-
Energy Consumption to maintain at operating temp ($\rho V C_p \frac{dT}{dt} \Delta T = Q_M$)	Btu x 10^6	-	-	-	0.155	8.004	-	0.352	-
Total Energy Consumption ($Q_H + Q_M = Q_T$)	Btu x 10^6	-	-	-	0.749	8.937	-	1.006	-
Rate of Energy Consumption ($Q_T/\Delta t$)[a]	millions of Btu per hour	-	-	-	0.15	1.2	-	0.20	-
Water Flow Rate Low/High	gal/min	-	-	-	225	-	35/225	225	35/225
Water Used	gal	-	-	-	1493 (hot)	110 (hot)	7345 (cold)	1500 (hot)	7345 (cold)

[a] To heat at 3°F/min requires ∿2.1 x 10^6 Btu/hour.

Cumulative Energy = 10.692 x 10^6 Btu
Cumulative Water = 17794 gallons
Cumulative Hot Water = 3055 gallons
Cumulative Cold Water = 14690 gallons
$Q_H = 2.139 \times 10^6$ Btu
$Q_M = 8.511 \times 10^6$ Btu

$$\text{Energy} \quad \frac{10.692 \times 10^6}{600.74} = 17{,}800 \text{ Btu/\# of cloth}$$

$$\text{Water} \quad \frac{17794}{600.74} = 29.6 \text{ gal/\# of cloth}$$

Using this definition the energy and water consumption per pound of cloth for the "average cycle becomes

Energy consumption per pound of cloth processed = 2/3 (17,800) + 1/3 (23,200) = 19,600 Btu.

Water usage per pound of cloth processed = 2/3 (29.6) + 1/3 (44.5) = 34.6 gallons.

TABLE C5. COMPARISON OF WATER AND ENERGY USE FOR THE SELECTED CYCLES

	Energy consumption per lb of cloth processed (Btu)	Water usage per lb of cloth processed (gallon)
Typical Cycle (with scour)	24460	32.6
Average Cycle (with scour)	23200	44.5
Average Cycle (without scour)	17800	29.6

Comparisons of the Results Obtained by the Two Methods

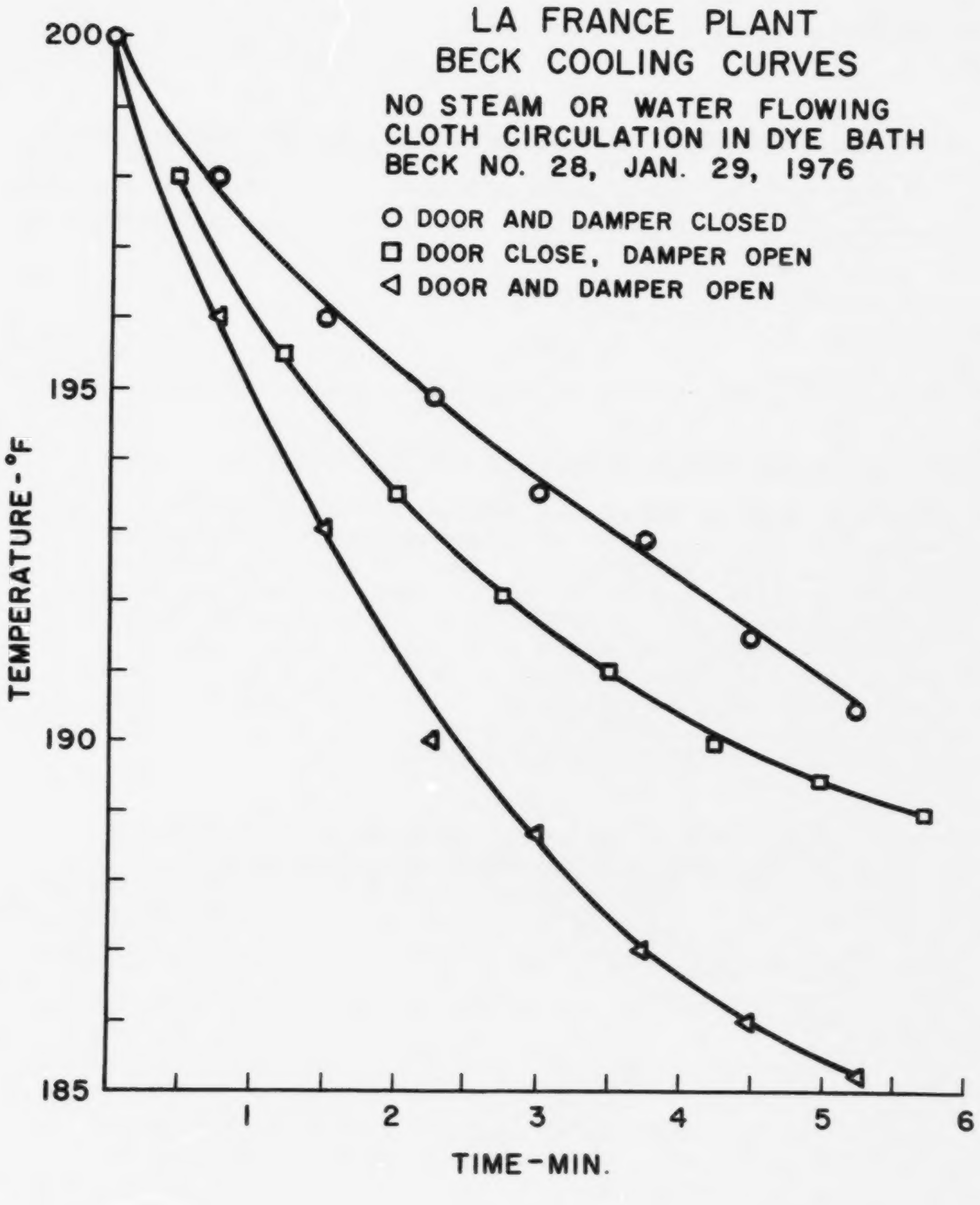
Table C6 compares the results obtained by the two methods. These two methods for the calculation of energy consumption per pound of cloth processed agree substantially. The discrepancy in the water usage figures can be explained by the fact that the rate and duration of the water usage in the cooling and rinsing phases of the cycle is not predetermined or automated; it is entirely left to the operator's intuition. For the lack of better information, we assumed that each cycle used cooling water at the high flow rate of 225/gal min for 30 minutes. These assumptions are partially justified by Figure C2 and the dyeing process description.

TABLE C6. COMPARISON OF THE ENERGY AND WATER USAGE PER POUND OF CLOTH PROCESSED AS DETERMINED BY THE TWO METHODS

	Energy consumption per lb of cloth processed (Btu)	Water usage per lb of cloth processed (gallon)
Method I (overall balance)	19170	53.7
Method II ("average" cycle)	19600	34.6

Losses

Losses from the becks are of two kinds: evaporation, and radiation and convection. The nature and significance of each of these will be discussed below.


LA FRANCE PLANT
BECK COOLING CURVES
NO STEAM OR WATER FLOWING
CLOTH CIRCULATION IN DYE BATH
BECK NO. 28, JAN. 29, 1976
○ DOOR AND DAMPER CLOSED
☐ DOOR CLOSE, DAMPER OPEN
◁ DOOR AND DAMPER OPEN
TEMPERATURE - °F
200
195
190
185
1
2
3
4
5
6
TIME-MIN.

Evaporation Losses — During the dyeing cycles steam is bubbled directly into the dye solutions to heat the beck contents to, and maintain them at, the required temperature. Since the becks operate at atmospheric pressure and near the boiling temperature for several hours per dye cycle, evaporation results in a large energy loss. This vapor escapes from the becks either by leakage or as a result of forced ventilation. Determined from the air flow rate and temperature and specific humidity data, this vapor loss amounts for more than two-thirds of the energy supplied to the dyehouse. The loss was confirmed by the overall dyehouse energy balance (Table C1) and can also be calculated from a heat loss/temperature plot (such as Figure A2) after the steam flow is stopped and before the cooling water flow begins. The rate of evaporation losses at any temperature can thus be determined from Figure A2 since the energy loss from the becks is mainly due to evaporation from the high-temperature contents. This loss can be considerably reduced either by replacing the atmospheric becks with pressurized units or by installing energy recovery equipment.

Radiation and Convection Losses — The radiation and convection losses are so significant (Table C1, relative to the evaporation losses) that purchase of equipment to reduce them may not be justified.

DISCUSSION OF RESULTS AND CONCLUSIONS

The results presented in Tables C1, C2, C3, and C4 show two things of great importance in this report. First is the large waste of energy because the dye becks are open to the atmosphere and operated for rather long periods of time at temperatures about 180°F. Evaporation of some of the hot water and the discharge of this vapor to the atmosphere accounts for about two-thirds of the energy supplied in steam to the dyehouse. This energy loss is not associated with the wastewater stream discharged to the sewer, but it is a tremendous amount of energy which may be conserved. The numbers in Table C1 indicate that, for fuel costing $2.75 per million Btu (delivered to the dyehouse), this energy loss amounts to more than $750 per day.

The second important factor is the large amount of energy discharged to the sewer in wastewater. Table C1 describes this as energy potentially available for reclamation, and Tables C2, C3, and C4 describe similar values as the "energy content of water in beck above 65°F" (including steam condensate). Though less than the evaporation loss, the loss in hot water discharged to the sewer is substantial. If the recoverable chemicals and water are included in the consideration, the daily cost of this wastewater becomes more nearly equal to that of the evaporation loss. The potential thermal energy recovery as indicated in Table C1 amounts to about $500 per day savings. This quantity is of primary interest in the present project.

APPENDIX D

ENERGY USE ANALYSIS OF A CONTINUOUS DYE RANGE

ENERGY CONSUMPTION BY PROCESS

This Appendix discusses the energy use of the observed dye range. Energy balances applied to the process equipment were made to determine the energy loss by evaporation from the wash tubs, the energy lost to the drain, and the energy recovered by means of the recovery heat exchanger.

Data

Data were required for water flow rates and temperatures for ten wash tubs used in the dyeing range. These data, given in Figure D1 were obtained as follows:

(1) Water flow rates were provided by plant personnel. A rotoameter-type flow meter was installed on the supply line to one wash box to confirm the reported flow rate.

(2) Water temperatures were measured using a hand held mercury-in-glass thermometer, a bimetal thermometer, or an iron-constantan thermocouple connected to a temperature recorder. Cloth temperatures were measured by holding the thermometer against the wet, moving cloth in places where there was sufficient water to give flooding of the sensing element.

Evaporative Heat Loss

Evaporative heat loss is a significant contribution to the total energy losses for the dye range. This latent heat loss is associated with (1) the evaporation from the water and cloth surfaces at the wash tubs, and (2) the evaporation from cloth surfaces as the cloth is transported between wash tubs.

The latent heat loss was measured in field tests as a function of water temperature as shown in Figure D2. A curve proportional to saturation pressure of water is fit through the data. This curve was used as the basis for the latent heat loss calculations for each wash tub.

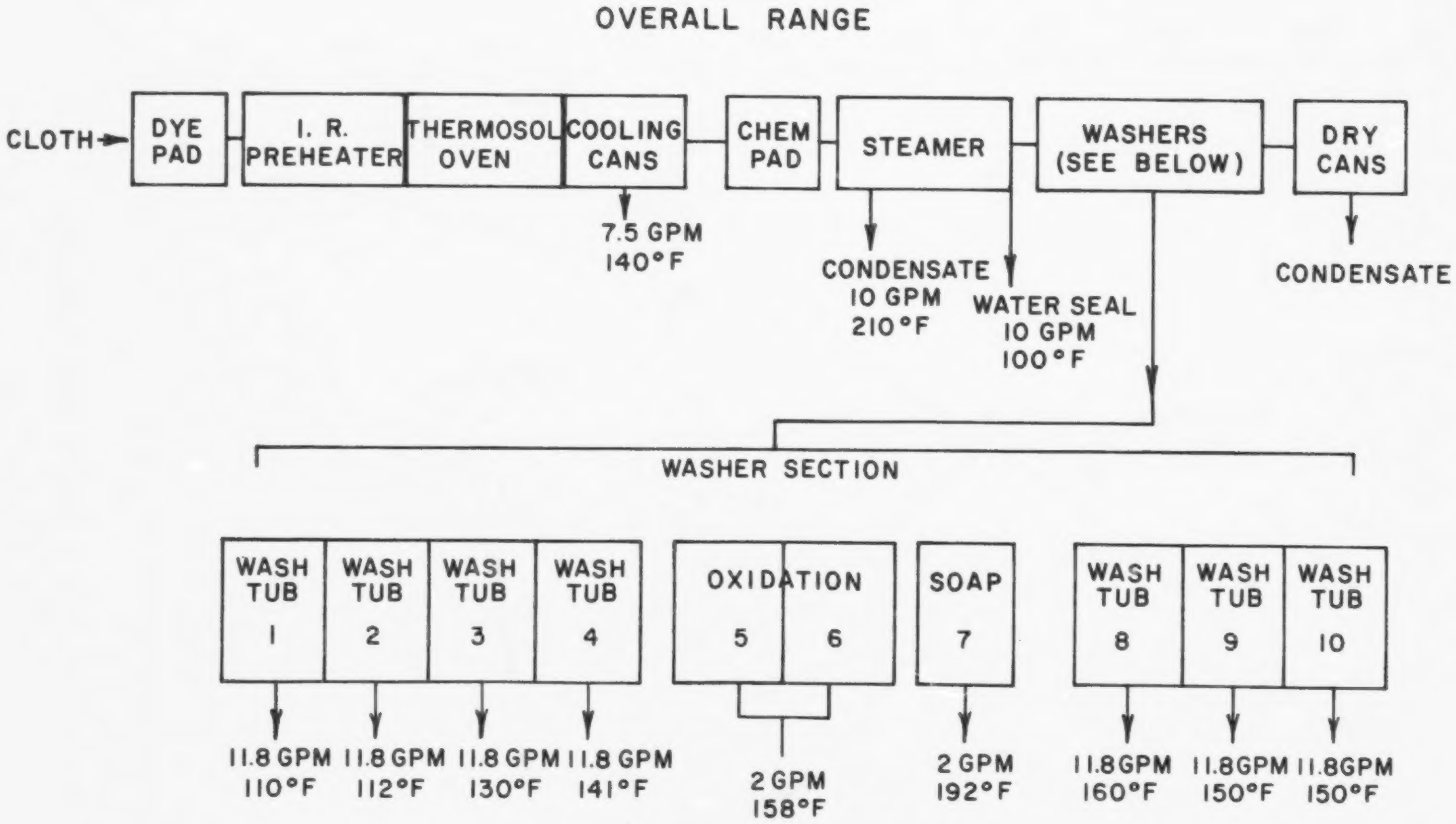

OVERALL RANGE
CLOTH
DYE PAD
I. R. PREHEATER
THERMOSOL OVEN
COOLING CANS
CHEM PAD
STEAMER
WASHERS (SEE BELOW)
DRY CANS
7.5 GPM 140°F
CONDENSATE 10 GPM 210°F
WATER SEAL 10 GPM 100°F
CONDENSATE
WASHER SECTION
WASH TUB 1
WASH TUB 2
WASH TUB 3
WASH TUB 4
OXIDATION 5 6
SOAP 7
WASH TUB 8
WASH TUB 9
WASH TUB 10
11.8 GPM 110°F
11.8 GPM 112°F
11.8 GPM 130°F
11.8 GPM 141°F
2 GPM 158°F
2 GPM 192°F
11.8GPM 160°F
11.8GPM 150°F
11.8GPM 150°F

FIGURE D1 SCHEMATIC DIAGRAM OF DYE RANGE

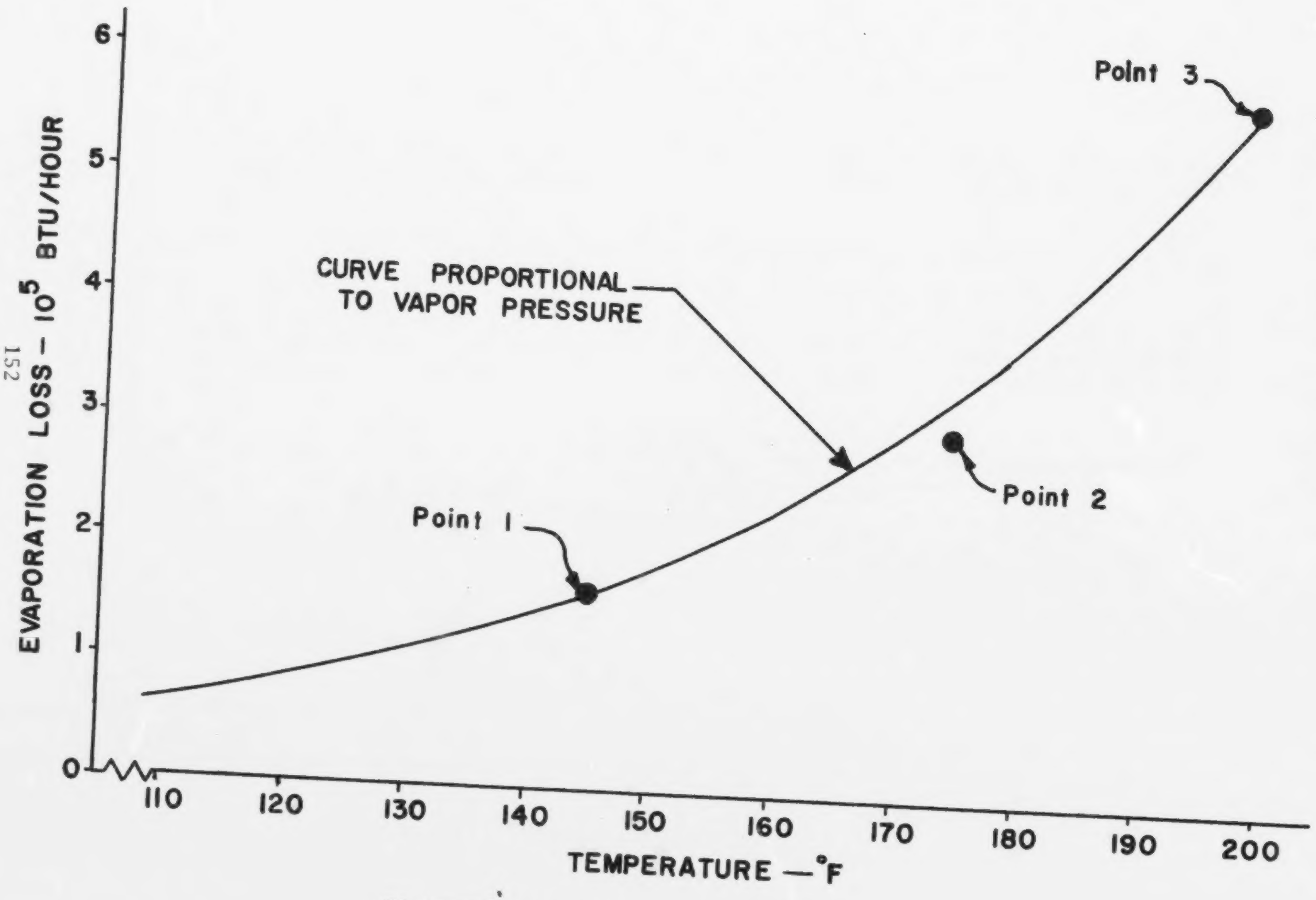


FIGURE D2 ENERGY LOSS BY EVAPORATION FOR DYE WASHERS

The specific data were obtained from two experimental procedures. The first procedure involved equating the temperature drop of the saturated cloth in moving from one tub to another at the rate of energy loss by evaporation. The temperature of the wash tub was adjusted by controlling the proportion of hot and cold water supplied to wash tub #8 so that the water entering and exiting the tub was at the same temperature (145°F). The energy in flow rate associated with the cloth entering from wash tub #7 can be equated to the loss from the wash tub. The observed temperature of cloth entering the tub #8 was 182°F. The loss of temperature from 192°F to 182°F was associated with evaporation between tubs, and tub #8 was credited with receipt of cloth and water at 182°F. Point 1 in Figure D2 was obtained by this procedure.

The second procedure was concerned with equating the cooling rate of a heated wash tub (#8) to the latent heat loss at the water and cloth surfaces within the wash tub. Steam was admitted to the tub to achieve a steady elevated temperature. Then the steam flow was terminated allowing the mass of fluid in the tub to cool. The total energy decline rate thus determined with no water throughflow can be equated to the loss by evaporation. Points 2 and 3 in Figure D2 were obtained by this procedure.

Using the heat loss schedule in Figure D2, an evaporative loss prediction for each wash box is shown in Table D1. There are entries thereon for operation at both standard procedure temperature and at the observed process temperature.

TABLE D1. EVAPORATIVE LOSS ESTIMATE

Wash Box	Standard Procedure Temp (F)	Evaporative Loss/Btu/hr	Observed Temp (F)	Evaporative Loss Btu/hr
1	120	86 x 10^3	110	64 x 10^3
2	120	86	112	68
3	120	86	130	112
4	120	86	141	148
5	135	128	158	224
6	135	128	156	213
7	190	466	192	487
8	175	335	160	235
9	175	335	150	184
10	175	335	150	184
Total		2071 x 10^3		1919 x 10^3

A certain amount of the total evaporative loss emanates from the section of cloth between the wash boxes. Covers on lids on the boxes would have no effect on this loss. Table D2 shows the predicted amounts of such loss for each washer connecting section for the observed operating temperature schedule. The basis for the calculation assumes an equal loss per unit of exposed wet surface and having the temperature trend of Figure D2. Such an assumption yields results which agree well with attempts to measure the temperature of the moving cloth surface.

TABLE D2. EVAPORATIVE LOSS ON CLOTH BETWEEN TUBS

Section Following	Evaporative Loss Btu/hr
Wash Box #1	6×10^3
2	7
3	12
4	15
5	23
6	22
7	51
8	24
9	19
10	19
Total	2×10^5

Energy to Heat Water

An estimate of the amount of energy used to heat water was obtained from the equation

$$q_{drain} = (\dot{m}c_p)_{H_2O} \; (T_{drain} - 65)$$

where q_{drain} is heat leaving the drain, $\dot{m}$ is the water flow rate, c_p is water specific heat, T_{drain} is drain temperature, and where 65°F is the assumed average annual temperature of the incoming fresh water. The energy loss to the drain thusly calculated from each wash tub is given in Table D3. The total amount of energy leaving the tubs was calculated as 3.156×10^6 Btu/hr.

TABLE D3. ENERGY REQUIRED TO HEAT WATER

Item	Observed Flow lb/hr	Observed Temp F	Energy to heat water Btu/hr
Wash Box 1	5897	110	2.65×10^5
2	5897	112	2.77
3	5897	130	3.83
4	5897	141	4.48
5	500	158	0.46
6	500	156	0.46
7	1000	192	1.21
8	5897	160	5.60

TABLE D3. (continued)

Item	Observed Flow lb/hr	Observed Temp F	Energy to heat water Btu/hr
Wash Box 9	5897	150	5.01
10	5897	150	5.01
Steamer Condensate	5000	210	7.25
Steamer Water Seal	5000	100	1.75
Total			40.6 x 10^5 Btu/hr
oven cooling water	3750	140	2.81 x ^{5} Btu/hr

Also shown in Table D3 are the contributions to an energy balance of the steamer condensate flow, water seal flow, and the cooling cans which follow the thermosol oven. The cooling cans represent an energy recovery from the cloth leaving the oven and thus do not contribute to the energy required for the range. The values for the water seal and condensate do represent heating requirements. The magnitude of the condensate flow of 5000 lb/hr implies that heat is lost sensibly in an amount of approximately 5 x 10^6 Btu/hr. This number is much larger than we believe can occur with air cooling and radiation from the steamer surface. Order of magnitude calculations suggest about 1.5 x 10^5 Btu/hr should be used to heat the cloth and water from 80°F to 210°F and perhaps 1 x 10^5 Btu/hr should be lost by direct losses to the air and surrounding environment. The flow measurement of the condensate drain may not have been accurate at the 10 gallons per minute rate shown in Figure D1 but is about twenty times as great as predicted above. Consequently, we allow the following options: (1) the observed flow was not a representative average condition, (2) the observed flow has other sources in addition to condensate, or (3) some very much larger than estimated heat loss mechanisms occur.

Table D4 shows a predicted heat loss rate for radiation and convection from the outer surface of the equipment to the surroundings. The prediction, from experience, is known to be complex and subject to considerable uncertainty. However, an upper bound calculation may be performed and predicts a fairly small loss compared with other energy items. This upper bound has used conventional convection heat transfer correlations at maximum probably air velocities and maximum radiative heat transfer coefficient. Such a procedure results in a composite upper bound heat transfer from the source to 85°F at an overall combined heat transfer coefficient of 2 Btu/hr-ft^2-°F (see Appendix B).

TABLE D4. ENERGY LOSSES BY RADIATION AND CONVECTION

Item	Energy Loss Btu/hr
Wash Box 1	0.53 x 10^4
2	0.57

TABLE D4. (continued)

Item	Energy Loss Btu/hr
Wash Box 3	0.96
4	1.19
5	1.56
6	1.51
7	2.29
8	1.61
9	1.39
10	1.39
Steamer	15.3
	28.3×10^4 Btu/hr

Energy Recovery

On a plant scale, energy recovery is effected by collecting the hot drains into a feed stream to the hot side of a heat exchanger. A hot water supply is provided at 150°F. About 35% of the hot water is heated in the heat exchanger to approximately 110°F, then is heated by steam to 150°F. The other 65% is heated by steam only. For an incoming temperature of 65°F, the heat recovery fraction of the hot water may be estimated. If $\dot{m}_f$ is the flow rate of 150°F water, the total energy added to the hot stream is

$$Q_{Total} = \dot{m}_f c_p \ (150 - 65),$$

while the energy supplied in the heat exchanger is

$$Q_{H/x} = 0.35 \ \dot{m}_f c_p \ (110 - 65).$$

The fraction of thte total amount supplied is the ratio or

$$\frac{Q_{H/x}}{Q_{Total}} = \frac{0.35 \ (110 - 65)}{(150 - 65)} = 0.185.$$

While the ratio is valid for the entire plant energy recovery, it does not adequately represent the particular dye range of interest.

To properly credit the energy recovered from the dye range, its contribution to the total recovery is estimated. The water from the condensate drain, wash tubs #8, #9, and #10 compose the hot drain from the range. All fluid collected from the various hot drain sources is cooled to approximately 95°F at the heat exchanger exit. Therefore, neglecting heat losses in transit from the individual drain to heat exchanger entrance, the energy recovered from each stream is

$$\dot{m}_i c_p \ (T_i - 95).$$

Here $\dot{m}_i$ is the mass flow of drain i at temperature T_i and is the more specific heat value. The sum of these energy recovery amounts for each "hot" drain is that amount credited to the dye range heat recovery. The amount is 1.6×10^6 Btu/hr for the above listed group of component drains. This represents 40% of the energy used to heat water on the range.

Results and Discussion for Energy Description

The emphasis here has been to identify the modes of energy loss and to determine the amount of heat which is recovered for the dye range. Energy losses by evaporation and radiation and convection and energy flow in the wastewater stream were examined.

The energy loss from the wash tubs by evaporation represents a relatively large quantity which could feasibly be conserved with an alternative equipment design. As shown in Table D2, the evaporative heat loss from all wash tubs was calculated at 1.92×10^6 Btu/hr. The evaporative heat loss from the saturated moving cloth surface as it was transported from one tub to another was only about one-tenth of the total energy loss by evaporation. (About 4.06×10^6 Btu/hr of energy was used to heat water from 65°F to process temperature and about 1.6×10^6 Btu/hr was recovered in the plant heat exchanger.) The energy loss by radiation and convection was only about 15% of the energy loss by evaporation.

The total energy loss minus the recovered energy was found to be 4.66×10^6 Btu/hr. The use of energy was as follows: evaporation losses (30%), net to heat water (65%), radiation and convection including steamer (5%). These values are depicted graphically in Figure D3 and tabulated in Table D5.

TABLE D5. ENERGY CONSUMPTION FOR DYE RANGE NO. 8

Energy Loss - Evaporation	1.92×10^6	Btu/hr
to heat water	4.06×10^6	
Radiation & Convection	1.30×10^5	
Steamer	1.53×10^5	
TOTAL	6.26×10^6	
Less Energy Recovered (from H/x)	-1.6×10^6	
Net Energy Supplied	4.66×10^6	

$$\text{Net Energy Consumption} = \frac{4.66 \times 10^6 \ \frac{\text{Btu}}{\text{hr}} \left(\frac{1 \text{ hr}}{60 \text{ min}}\right)}{61.5 \ \frac{\text{lbm cloth}}{\text{min}}} = 1262 \ \frac{\text{Btu}}{\text{lbm cloth}}$$

CONTINUOUS DYE RANGE

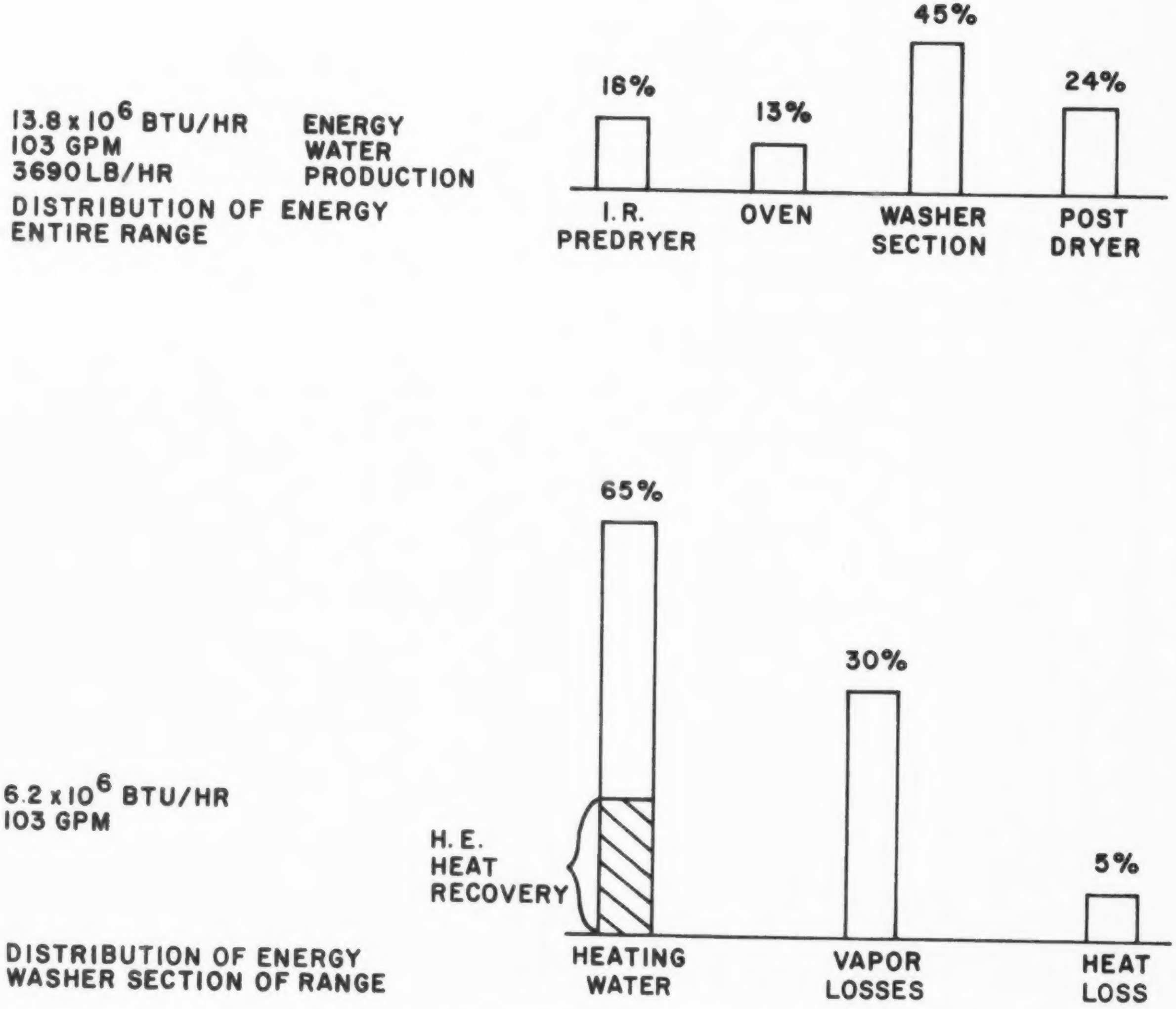


FIGURE D3 DISTRIBUTION OF ENERGY ON DYE RANGE

The above values are for the wet portions of the dye range. The entire range from the pre-dryer through the dry can post-dryer consumes an amount estimated as 7.5 x 10^6 Btu/hr in addition to the amounts already delineated. Thus, the wet processes only include approximately 45% of the total energy supplied to the range.

Conclusions for Energy Description

Evaporation from the water and cloth surfaces of the wash tubs amounted to 14% of the total energy lost in the dye range. Since this evaporation is a direct loss to the plant and represents a significant item for energy savings it should be minimized. Proper equipment design that provides for covered wash tubs would decrease evaporative energy losses.

Almost two-thirds of the wet portion energy is lost to the drain and represents the largest area for energy and cost savings. The potential for energy conservation by recycling water is significant. If only 80% of the energy now used to heat water could be recycled in the dye range, the energy savings would be about 3.2 x 10^6 Btu/hr. As the system now operates only 1.6 x 10^6 Btu/hr is being recovered to heat incoming fresh water.

There are two relatively inexpensive energy savings devices apparent from the analysis conducted associated with this report. These are the addition of tub covers and the rerouting of one of the drain lines. Our analysis results in an evaportion heat loss of 1.92 x 10^6 Btu/hr from the tubs, with 10% of this or 0.2 x 10^6 Btu/hr associated with the cloth between tubs. Covers over the tubs would reduce the heat loss up to 1.7 x 10^6 Btu/hr. We are not able to estimate the effect of an imperfect cloth seal on the approach to this value stated.

The water drain from the cooling cans following the thermosol oven constitutes nearly the flow supplied to one wash box and was observed to be at 140°F. This water is clean and has some head allowing it to be routed to provide flow to one of the tubs. A saving of 40,000 Btu/hr is expected to result (or 80,000 Btu/hr if the flow does not contribute to the heat recovery system).

The steamer condensate represents an additional energy source. Depending on its quality with respect to the quality required for wash water, it could be pumped into a tub directly at a savings potential of over 300,000 Btu/hr. We tend to believe this number is not representative of steamer actual condensate rate, so the matter should be investigated further.

Based on data received from plant personnel, the use of the Max Trac urethane roller prior to the dry cans would decrease the energy flow an estimated 1,800,000 Btu/hr. This estimate assumes a water content of 0.7 pounds for the standard roller versus 0.3 pounds for the improved roller per pound of cloth. At a cost of \$7000 for the roller and \$2 per 10^6 Btu for energy, the roller should pay for itself in under 2000 hours. In future installations the superior roller will allow the use of half the number of dry cans or fewer and better drying control with less dye migration or anti-migration chemical. Thus, a new installation should be both cheaper overall and have substantially lower energy requirements. In present installations the urethane roller probably should be implemented along with a reduced number of active cans. The unused cans should be unheated and removed from the cloth path. This would provide for a minimum of direct heat loss from the cans.

APPENDIX E

ANALYSIS OF MASS REMOVAL FROM CLOTH IN PREPARATION

It is desired to remove as much as possible of the warp sizing from material in preparation while using a minimum of water and equipment. The presence of substantial amounts of size in the water wash and chemical desize wash of the open width preparation range has been shown in the text of this report. Herein an investigation into the completeness of the removal from the cloth is considered.

The cloth considered was a 65/35 polyester/cotton blend with a size composed of PVA, CMC, and sizing wax. Other substances may also be present: spinning oils, natural waxes, and dissolved or removed motes. The total amounts removed by a boiling exercise for 15 minutes in detergent were 9% by weight of fabric.

A simple exercise at graduated boiling intervals up to 5 minutes showed that essentially all material may be removed in 30 seconds to one minute at boiling conditions. By using a mild Freon extraction, the sizing wax could be selectively removed from the cloth, leaving the CMC and PVA. Thus it was possible to separately analyze for the removal of wax and PVA/CMC.

Cloth samples were removed following the first washer (water washer) and following the chemical desize washer. Selective weighings show that the removal of wax are 12 and 25% respectively in these two steps. Also 58 to 39% of the PVA/CMC are removed by these two steps. Thus the sizing wax persists to the caustic washer and only 3% of the PVA and CMC persist to the caustic washer.

APPENDIX F

OPTIMIZATION COMPUTER PROGRAM

This facet of the Energy Project is concerned with the development of a computer program to evaluate the relationship between operating parameters and net cost for a hyperfiltration system. For known resource values and given operating conditions, this program was conceived to seek out the greatest profit or least loss to the operation. The validity of the discovered optimum must be scrutinized in light of the assumptions made to model mathematically the hyperfiltration process. It is the purpose of this section to outline those assumptions, in particular the definition of the assumed hyperfiltration system, the economic simplications, and the method of characterizing the membrane performance. A brief discussion of the means of optimization and an overview of some of the results will also be presented.

The hyperfiltration system which has been modeled is schematically illustrated in Figure F1. Depicted is an industrail process which produces chemically contaminated wastewater that may include chemicals, detergents, dye and other wastes not necessarily limited to those generated by the manufacture of textile goods. This wastewater is the input to the hyperfiltration system. The desired outputs may include reuseable water, reclaimed chemicals, and heat. At the heart of the assumed hyperfiltration systems is a tubular module that separates soluble chemicals into dilute (permeate) and concentrated streams. The module consists of a series of tube bundles acting as porous supports for the membrane which is deposited on the tubes. Two pumps are in the hyperfiltration systems, one for primary flow and the other to recirculate concentrate flow so that is might be brought to a higher concentration. An evaporator completes the array of equipment in the hyperfiltration system. The evaporator further concentrates the solutes in the stream so they may achieve value as reclaimed chemicals. The hyperfiltration system assumed in this study then consumes contaminated water, electrical power for pumping, and thermal energy for evaporation; it produces clean water, reclaimed chemicals, and recoverable heat.

The portion of the computer program that assesses the net cost of operation is an attempt to characterize only the five most prominent expenditures or benefits. The costs are divided into two groups, capital costs and operating costs. Capital costs are limited to expenditures for the tube module and the pumpage. The cost of the evaporator is not included in this study. The cost of dollars per tube includes

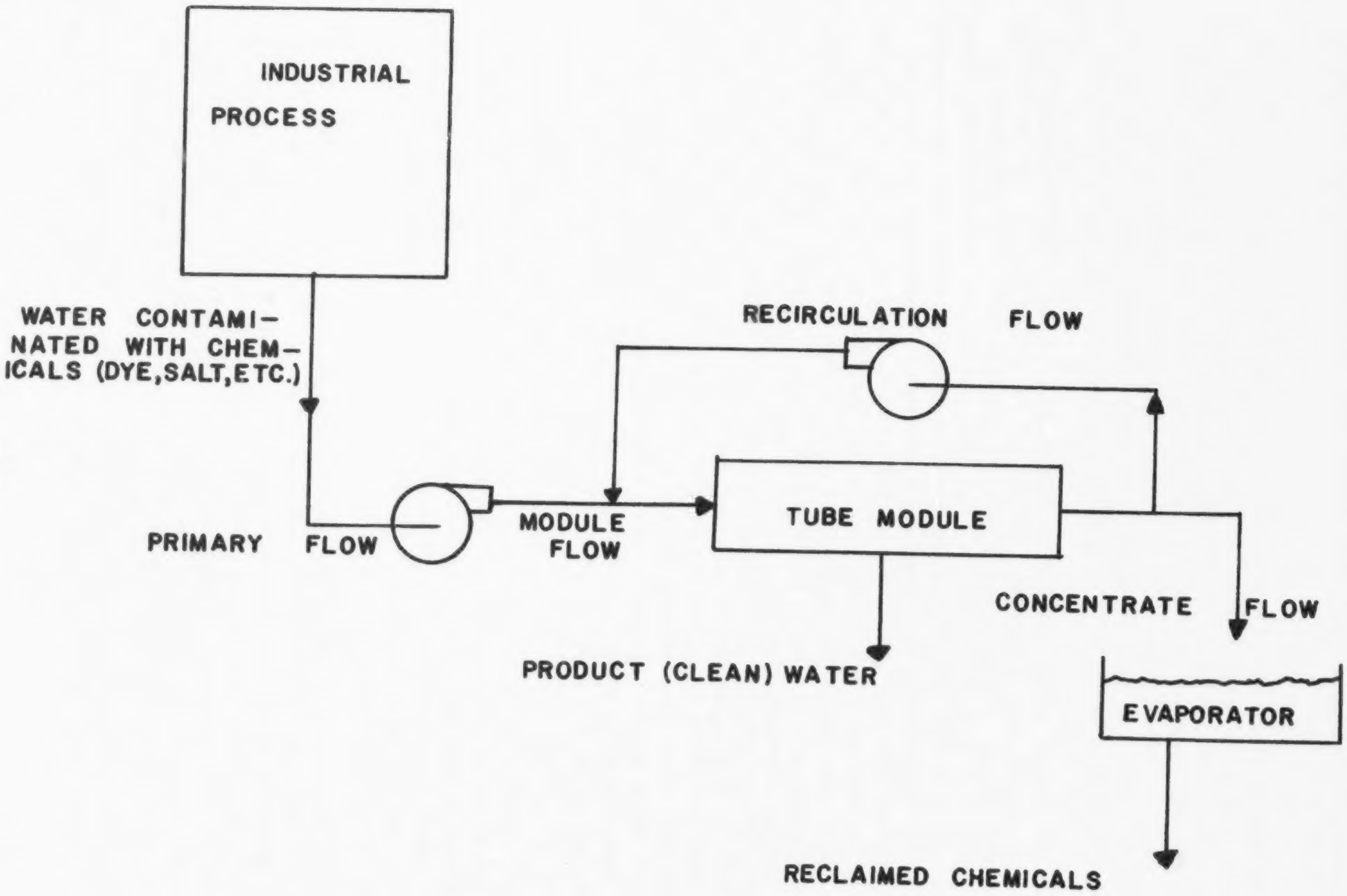

INDUSTRIAL
PROCESS
WATER CONTAMINATED WITH CHEMICALS (DYE, SALT, ETC.)
PRIMARY FLOW
MODULE FLOW
RECIRCULATION FLOW
TUBE MODULE
CONCENTRATE FLOW
PRODUCT (CLEAN) WATER
EVAPORATOR
RECLAIMED CHEMICALS

FIGURE F1 SYSTEM DESCRIPTION

the averaged cost of the tube, membrane, housing, and fittings for the module and is an input quantity, i.e., \$45/tube. The cost for pumps is assumed proportional to the power required, i.e., pressure rise multiplied by primary flow plus recirculation pressure rise multiplied by recirculation loop flow. The constant of proportionality is input, i.e., \$X/kilowatt.

Operating costs are figured as dollars per day. The optimum cost function, which is in dollors, is calculated on the assumption of a 300-day operating period. Therefore, an optimum cost of zero indicates that after 300 days of operation the initial cost and operating costs were exactly offset by savings of chemicals, water, and/or heat. A negative optimum reflects a benefit to the operator, and a positive number reflects a deficit.

Of the three operating costs, the first is for the consumption of electrical power by the pumps. This cost is proportional to the number of kilowatt hours required for a day of pumpage with the constant of proportionality input, e.g., .013 dollars per kilowatt hour. The other two operating costs reflect savings through clean water and recoverable heat in the product flow stream and reclaimable chemicals in the concentrate flow stream. For savings associated with the product stream, a credit is assigned for both clean water and its associated thermal energy, and the credit is negated if the product water contains excessive concentrations of solutes. Recoverable thermal energy here refers to fluid having temperature above 293°K. The savings associated with reclaimable chemicals in the concentrate flow is examined on a solute-by-solute basis and summed over all the solutes. If a solute in the stream has a concentration equal to or higher than the desired concentration for reclamation, then that solute is credited in dollars per kilogram with the full value of reclamation. If, however, a particular solute has a lower concentration than that desired for reclamation, it must be evaporated until the concentration reaches a reclaimable value. The dollars per kilogram credit is accordingly reduced by the cost of energy input for evaporation. If the cost of energy needed for evaporation to concentrate a particular solute is more than a solute is worth, then the solute is not reclaimed and the savings for that solute is zero. This analysis assumes that there is no cost of separating solutes and that no heat is reclaimed from the concentrate stream even if no evaporation is needed. The investigation at Clemson has assumed up to six solutes in the primary flow.

The mathematic modeling of the performance for the membrane is accomplished by accounting for the influence of temperature and pressure on the membrane flux and the influence of velocity and pressure on the intrinsic membrane rejection. Flux is the term used to describe amount of product flow per area of membrane. A flux representative of real membranes examined at Clemson operating at 349°K and 6.5×10^6 Pa (950 psi) is input at the beginning of the program. This flux is modified by a pressure function and a temperature function. The temperature modification is of exponential order with higher temperatures yielding larger fluxes. The pressure modification is linear with higher pressures also yielding larger fluxes. The temperature of the primary flow is a constant that is input at the beginning of the program and does not change from section to section in a single design or from design to design. The pressure used to evaluate the pressure modification is that at the inlet of each section of tubes. This pressure changes from section to section and from design to design.

Rejection is a term that describes how efficiently a membrane separates solute and solvent. A membrane rejection is input at the beginning of the program for each of the solutes in the primary flow stream. These rejection values, characteristic of membrane behavior at high operating pressures, are modified by a pressure function and a velocity function. The pressure function is such that at high operating pressures the rejection values tend to approach the input values, and rejection drops off slightly as the pressure tends toward zero. The velocity modification assumes one of two values for each velocity, depending on whether the Reynolds Number indicates a turbulent or laminar condition for the primary flow through that section of tubes. The turbulent case results in smaller fluxes at high velocities and larger fluxes at lower velocities than the laminar case does. The rejection is reduced in both cases for high velocities due to concentration polarization. The pressures and velocities used for the rejection value modifications are those existing in each section and therefore are subject to change from section to section. The nature of the pressure modification of solute rejections has its analytical basis in the Onsager equations, the coupling between solute and solvent fluxes, and the distribution coefficient.

Optimization

Optimization is initiated by defining certain input parameters. The cost function to be optimized depends upon these input parameters that are left as "floating" variables. These variables are given an arbitrary value that will be changed as the program iterates and seeks the lowest possible cost. For the purpose of this program, four variables are designated as floating variables, and they form a four-dimensional space within which the cost functions will be optimized. The four variables are the system recovery (REC), which is the ratio of product flow to primary flow; the recirculation ratio (RERAT), which is the ratio or recirculation flow to primary flow; pump outlet pressure (POUT), which is the pressure directly upstream of the tube module; and VELMIN, which is the velocity as near upstream of each tube as possible.

The main program controls the optimization process and assigns starting values to REC, RERAT, POUT, VELMIN. The main program also determines the incremental step size for each variable that will be taken in a positive and then a negative direction from the initial operating point. Only one variable has a constant step size: VELMIN, at 0.1 meters per second. The other three step sizes are calculated at each step and are not necessarily constant. The technique employed in the optimization code is a straight-forward hill-climber. An operating point in four-variable space is assigned, and, with three variables held constant, the fourth is perturbed slightly in a positive direction and then in the negative by the amount of the step size. The three values of the perturbed variable are sent to the subprogram SOLUTE one at a time. SOLUTE establishes a separate module design according to the specifications demanded by each value of the perturbed variable. A total cost is evaluated for each of the three module designs and sent back to the main program for analysis. The main program examines the three costs, ascertains the lesser of these, and adopts the value of the variable that produced the lower cost design as the new operating point. The main program then cycles to the next of the four variables and repeats the procedure. An optimum is determined when none of the perturbations around the operating point in any of the four floating variables produces a module design of lower cost. The main program then signals the user that only higher costs exist in the vicinity of that operating point, which is therefore a minimum.

An important aspect of the optimization process is the method by which the module design is established. The tube module is developed from inlet to outlet by calculating the number of tubes that are needed to handle the flow at each section. The flow that presents itself at the inlet of the module is a sum of the primary flow and the recirculated flow. The number of tubes required in the first section is calculated by the equation:

$$\text{tubes in a section} = \frac{\text{flow at inlet}}{\text{cross sectional area per tube x minimum velocity}}$$

This calculation is not based on the actual velocity in that section but on the minimum velocity (VELMIN) input from the main program. The actual velocity is calculated and used in the mass transfer equations to arrive at the amount of product flow produced by the first section of tubes. This product flow is subtracted from the inlet flow to arrive at the amount of flow going into the second section. The number of tubes for the second section is calculated by the above equation using the same value of minimum velocity. This process is iterated, and the result is a number of tube bundles in series that form the module. A design is finally arrived at when enough sections of tube bundles exist to produce the amount of product water demanded by the recovery ratio.

Of course, there have been some problems in the development and application of this program. It was early discovered that the cost function was not smooth but contained many peaks, cliffs, and holes, mostly because sharp cutoff values were used to regulate the peripatetic wanderings of some variables and functions. This problem was solved by introducing smoothing functions with gentle incentives not to wander too far in certain directions. Another continuing problem is the discretization of the number of tubes in a section; that is, a section contains only an integral number of tubes and cannot accommodate 1/2, 3/7, or any fraction of tubes. This leads to small steps in the cost function but is estimated not to deter the hill-climber optimization technique from finding a minimum. It does, however, eliminate the use of a faster, more efficient optimization technique based on the directional derivative. A third problem is that the program may seek a local "false" minimum and not the ultimate minimum located within the search domain. As yet no means exists to tell a false minimum from the ultimate minimum except to try many starting places and compare the discovered minima.

The computer program has been exercised only a modicum due to two factors. First, the program was constructed assuming the input of an acceptable permeate quality. All permeate water has been decreed reusable by plant personnel based on their experience and laboratory tests described herein. Thus the limit has not been reached. Because most of the intricate details of the optimization procedure are related to water quality the lack of a quality limit specification causes the bulk of the exercise to have no meaning.

Second, the main design problem of optimizing costs to achieve a known water production has not been modeled. Since the flux dependence on concentration velocity, pressure, and temperature is pronounced a much more profitable exercise could be conceived. Such a program would have been beneficial in the design section of this report.

Despite these shortcomings, the program indicated some general trends. The effect of recirculation on water quality is disasterous, even in small amounts. Only when perfect (>99%) rejection is achieved or when permeate contamination is unimportant will recirculation be tolerable. The recovery of material in concentrated form will be diminished also by recirculation.

High pressure operation is indicated to be attractive. Partly this is due to the short (300 day) evaluating period which tends to decrease the relative operating cost penalty compared with the capital outlay.

A factor not evaluated but pertinent is the estimation of temperature effects. The use of high recovery recycles a major part of any energy increment. Processes may benefit by higher temperature as well and the cost is nearly exclusively tied to increased evaporation. The appropriate question is, does the decreased cost of membrane installation pay for the increased energy cost of evaporation? An appropriate evaluation must include the flow versus temperature for the process itself.

APPENDIX G

TEXTILE WASHING STUDY

The evaluation of washer technology is a logical complement to an evaluation of hyperfiltration for wastewater reclamation. Primarily this is true because improved washer operation will reduce water consumption without reducing washed off solids. The cost of membrane filtration is estimated to be roughly proportional to the water flow and the reclamation benefits are proportional to the concentration of reclaimed material. Even without the implementation of membranes, process efficiencies can benefit immediately by enhanced washer technology.

A survey of washing equipment manufacturers concerning their design information and field experience has been completed. Information herein is primarily resulting from the following companies: Gaston County Dyeing Machine Corporation, B-K Textile Machinery, Morrison Machine Company, and Menoyama Kiko Company Limited.

Copies of various technical papers pertinent to the present investigation have also been accumulated. Olson and Lyons[8] showed the effect of heat setting on the polyvinyl alcohol size removal fraction. The study indicated an outstanding effect of wash water temperature. Parrish[9] also has studied the effect of wash water condition on the removal of NaOH. The tendency of industrial plants toward counterflow washing also suggests that mathematical modeling could be beneficial.

Washing involves removal of sizing materials, scouring, bleaching, and rinsing the cloth. Washing effectiveness is determined by the amount of material removed from the cloth in the washing process.

Dry cloth enters a desize washer to remove sizing material, wax, and other lubricants added to the fabric strands during weaving. The water in the desize washer contains surfactant to reduce surface tension and allow penetration of water into the cloth. If the cloth is a polyester blend that uses either PVA or CMC as the lubricant then desizing is not necessary and scouring would be the first cloth operation. If the cloth is cotton or a cotton/polyester blend, then starch is generally used as a lubricant and either enzymes or HCl are added to the wash water in the desize operation to chemically break down the starch in preparation for scouring. PVA and CMC are at least soluble in water while starch is not soluble. Presumably the sugars such as fructose produced from the starch are soluble in the water.

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[8] Olson, E. S. and D. W. Lyons, "Effect of Drying and Heat Setting Temperatures on the Removal Characteristics of Polyvinyl Alcohol Size," Textile Research Journal 42, 4, pp 199-202, 1972.

[9] Parrish, G. J., "Continuous Rinsing of Impurities from Textile Fabrics," American Dyestuff Reporter, Vol. 54, No. 5., pp 33-39, May 1965.

The effectiveness of the washer can be measured in terms of the concentration of sizing on the fabric before and after the wash period. This is expressed as

$$\Sigma = 1 - \frac{C_{2_i}}{C_{1_i}}$$

where

C_2 = concentration of sizing (i) on fabric as it leaves the tub
C_1 = concentration of sizing (i) on fabric as it enters the tub

The effectiveness varies from 0 when $C_{2_i} = C_{1_i}$ (the water has not changed the concentration of sizing on the fabric from what it was initially) to 1 when $C_{2_i} = 0$ (all the sizing has been removed from the fabric).

The physical processes that occur in the washing operation are:

(1) Dry cloth with sizing is dumped into a tub of flowing water containing surfactants. The sizing is located only on the cloth surface due to its high molecular weight (PVA = 100,000, starch = 200,000). Usually the concentrations of PVA are about 6% on the cloth surface, while starch will have an initial concentration of about 15%.
(2) Droplets of about 1/8 inch diameter are formed on the cloth surface due to surface tension. The contact angles for water on cloth depends on the type of cloth and can be 0° for cellulose and as high as 20° for polyester. The surface tension constant for water on cellulose is 42 dynes/cm while water on polyester is 31 dynes/cm. Surface tension is an important phenomenon and can delay penetration of water into the cloth by five to seven minutes for cloth suspended in a stagnant water body.
(3) Water is absorbed by the cloth as surfactants reduce the surface tension at the cloth surface. The ability for materials to absorb water is highly variable and ranges from 17% water in wool, 6.5% in cotton, 4% in nylon, and .5% in acrylics.
(4) Enzymes in water such as α- and β- amylases break down starch by chemical reaction. If PVA is on the cloth it is in crystalline form from heatset treatments at 150°C. Both PVA and CMC are hydrogenzied in the water and form a concentrated film of large

positions has its own advantage, though the laboratory approach probably is the only way to achieve truly different results from those being observed at present.

It appears that mathematical modeling of a group of washers could be used to profitably evaluate the effect of counterflow. The model would use overall washer performance data from the field as a basis. The modeling of a single washer is not as simple and would require either additional laboratory work or field data to substantiate it. It is considered beyond the scope of the present work to attempt such a model.

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